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Aerial view southeast down San Andreas rift valley	Frontispiece

FRONTISPIECE. Aerial view southeast down San Andreas rift valley, which is occupied by Crystal Springs Lakes, San Mateo County. Old fault scarps and troughs may be seen in the linear en echelon arrangement in the center background leading off from the right side of Upper Crystal Springs Lakes. *Photo by Clyde Sunderland, Oakland*

PREFACE

The San Francisco earthquake of March 22, 1957 was a minor one in an area long known to be seismically active. Nevertheless, it was the strongest and most damaging shock San Franciscans have felt since the great earthquake of April 18, 1906. Although quite different in the amount of energy involved, nature of earth movement, and geologic surface effects, both apparently originated on the same segment of the San Andreas fault. This fault—California's most widely known structural geologic feature—has a history of repeated displacements which have caused many earthquakes along its 650-mile length in the State; doubtless it has been intermittently active for many millions of years in late geologic time.

The Division of Mines, in performing its function as the State's public information bureau on geology, mineral resources, and the mineral industries, investigates and reports on geologic phenomena. An increasingly large number of inquiries in recent years has centered on faults and earthquakes; in particular, on the San Andreas fault. This Special Report attempts to answer some of these inquiries by presenting, under one cover, the results of cooperative studies of San Francisco's March 1957 earthquake, conducted by seismologists, geologists, and engineers.

Shortly after the March 1957 shock, representatives of the cooperating agencies met in the offices of the seismology section of the United States Coast and Geodetic Survey to discuss the broad coordination of investigations in the special fields of each. The Coast and Geodetic Survey contributed results of their strong-motion seismologic studies and triangulation surveys, the Universtiy of California summarized seismic history of the area and reported on seismographic results, the United States Geological Survey discussed observations and mapping by their engineering geologists, damage to structures was investigated by engineers of the Pacific Fire Rating Bureau and by the Division of Architecture, and an analysis of building motion was made by mechanical engineers of the California Institute of Technology. The Division of Mines contributed information on the areal geology of the fault zone, acted as coordinating agency in enlisting and handling the various contributions, and compiled and edited this Special Report.

In addition to the contributing authors who are named in the text, the editor is grateful to many others who responded generously to requests for information or aid appropriate to their special knowledge or associations. Among these are: Dr. Gladstone B. Marchand and Captain F. F. Kravath of the Twelfth Naval District who furnished the excellent aerial photographs incorporated in the introductory paper; Richard J. Woodward and John A. Trantina of Woodward, Clyde and Associates who furnished soil and foundation data for part of Westlake Palisades; Henry Doelger, Builder, Inc., and Theodore V. Tronoff for information on houses in Westlake Palisades; and Lew Wulff of the Division of Highways who contributed a note on soil conditions in the Westlake Palisades area.

Gordon B. Oakeshott
Chief, Division of Mines

San Francisco
October 1, 1958

SAN ANDREAS FAULT IN MARIN AND SAN MATEO COUNTIES

By Gordon B. Oakeshott
Geologist and Chief
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ABSTRACT

The San Andreas fault is probably the most widely known structural geological feature in California because it has been the source of so many earthquakes and because its topographic expression is so striking. The most damaging shock California has yet known, the earthquake of April 1906, as well as the earthquake of March 1957, have both centered in the San Andreas fault zone. In the San Francisco Bay area the fault is easily traceable across Marin County between Tomales and Bolinas Bays, is obscured by the ocean as it passes west of San Francisco, and is again prominent as it traverses the valley of the Crystal Springs Lakes of San Mateo County.

Striking N. 35° W. over much of its length, the fault divides San Mateo and Marin Counties into two geologic provinces—the Montara-Point Reyes block on the west underlain by Cretaceous granitic rocks, and the San Francisco-Marin block on the east underlain by slightly older (?) marine sedimentary, submarine volcanic and basic intrusive rocks which all belong to the Franciscan group. A subparallel, probably related fault, the Pilarcitos, forms the dividing line between these major structural units of "basement" rocks on the San Francisco peninsula.

The exact history and true complexity of movements along the San Andreas fault are not known. Geologic evidence is so varied that geologists have drawn conflicting interpretations of the geologic history and characteristics of the fault; at one extreme are those who believe that there has been several hundred miles of right-lateral, strike-slip displacement since late Jurassic time, and at the other are those who consider that there has been large vertical displacement on an ancestral San Andreas fault, and relatively small lateral displacement in late Tertiary and Quaternary time.

Major faulting of large displacement, with the western block apparently upthrown, took place after deposition of Paleocene rocks on the San Francisco peninsula and before deposition of the lower Miocene Vaqueros formation. The fault developed was the Pilarcitos, later folded near Pilarcitos Lake to form the Pilarcitos "thrust." Southward, this fault merges with the San Andreas fault zone, as it probably does also on the north. Franciscan rocks of the western block were extensively removed by erosion during late Paleocene to upper Eocene time, thereby exposing the underlying granitic rocks of Montara Mountain and Point Reyes.

After an epoch of quiescence and marine deposition during the Miocene, activity was renewed at the end of the Miocene. This activity was accompanied by development of a ridge extending the length of the San Francisco-Marin block. During the rise of this block the middle to upper Miocene Monterey formation was removed.

Whether these two great epochs of displacement on the ancestral San Andreas fault—pre-Miocene and post-Miocene—were predominantly vertical or horizontal, or were vertical in the first instance and horizontal in the second, cannot be determined in the present state of knowledge of the geology of the West Bay.

The early upper Pliocene to mid-Pleistocene Coast Ranges orogeny initiated movements on the modern San Andreas fault, and formed many present-day geologic, topographic, and drainage features of the East Bay and West Bay areas. The wonderful features of the rift zone, including Tomales Bay, San Andreas and Crystal Springs Lakes, and the numerous sag ponds and minor topographic peculiarities in the rift were developed at this time and modified in the latest Quaternary. Analysis of the nature and amounts of fault displacements in the San Andreas fault zone after deposition of the upper Pliocene-lower Pleistocene Merced formation and before 1906 is difficult because all the later structural features, including the modern fault zone, closely follow the north-northwest trend previously developed. Certainly there have been repeated displacements on near-vertical fault planes within the fault zone, the greatest in historic times being the 21-foot right-lateral surface offset at the south end of Tomales Bay in 1906, and the latest, a small, vertical (?) displacement at shallow depth which caused the earthquake of March 22, 1957.

LOCATION AND EXTENT

The San Andreas fault is probably California's most widely known structural geologic feature. It is certainly the greatest active fault of historic time—both the longest, and the one on which earthquakes have originated most frequently. The San Andreas rift zone has been traced for over 650 miles, from Point Arena to the Salton Sea in Imperial Valley. North of Point Arena, the ground was ruptured near Shelter Cove in Humboldt County during the San Francisco earthquake of 1906, suggesting a northward continuation of the fault under the Pacific Ocean between Point Arena and Shelter Cove. North of Shelter Cove, locations of earthquake epicenters give evidence of probable continuation of the fault zone under the ocean northwest of Cape Mendocino. Throughout its length, the fault zone is very clearly marked topographically by a series of narrow valleys, bays, small elongated lakes, sag ponds, and saddles; and geologically, by notable differences in rock types found exposed in certain areas on opposite sides of the fault.

From Point Arena, the fault extends approximately S. 35° E. along Tomales Bay and enters the ocean again at Bolinas Bay. It does not cross the city of San Francisco but continues offshore, underwater, and appears on land again at Mussel Rock, just north of Sharp Park. San Andreas and Crystal Springs lakes, on the peninsula, lie in the rift zone, and the fault extends southeastward through San Juan Bautista, Parkfield, the Elkhorn Hills, crosses the Ridge Route at Gorman, and continues via Palmdale, Cajon Pass, Imperial Valley east of the Salton Sea, and probably into Mexico.

There are two major breaks in the northwesterly trend of the San Andreas fault in southern California—one at its junction with the Garlock-Big Pine fault in the Ridge Route area near Frazier Park and Gorman, and the other in the San Gorgonio Pass area. In each place, strike of the San Andreas fault changes rather abruptly to due east and the fault zone is interrupted by major east- and west-trending faults. A similar zone of west-trending faults, transverse to the San Andreas, may account for the great Mendocino escarpment extending under the ocean west of Cape Mendocino in northern California.

FIGURE 1. San Andreas fault zone in California.

HISTORY OF GEOLOGICAL INVESTIGATION

Credit for first recognition of important faulting in the San Andreas zone on the San Francisco peninsula probably belongs to the late Professor A. C. Lawson of the University of California, who in 1893 said:

"The line of demarcation between the Pliocene and the Mesozoic rocks, which extends from Mussel Rock southeastward, is in part, also, the trace of a post-Pliocene fault. The great slide on the north side of Mussel Rock is near the land terminus of this fault zone, where it intersects the shoreline. Movement on this fault is still in progress. A series of depressions or sinks, occupied by ponds, marks its course. Modern scarps in the Pliocene terrane are features of the country traversed by it."

In 1899, F. M. Anderson, a student of Lawson's, recognized important faulting on the Marin peninsula, commenting that: "——evidences of faulting along the Baulinas-Tomales Valley are to be seen both in the topography and in the general stratigraphic and petrographic relations." Anderson thought this fault connected with the fault described by Lawson along the western margin of San Bruno Mountain; not the major fault in the zone occupied by San Andreas Lake. Neither Lawson nor Anderson gave a name, at that time, to the fault zone. The Fifteenth Annual Report of the U. S. Geological Survey contains a colored geologic map of the San Francisco peninsula (Lawson, 1895, p. 399-476) and an account of the geology.

The great San Francisco earthquake of 1906 focused attention of leading California geologists of the day on the fault zone responsible, and resulted in publication of the monumental report of the State Earthquake Investigation Commission (A. C. Lawson, editor, 1908) in two volumes and an Atlas. Lawson, assisted by such prominent American geologists as G. K. Gilbert, J. C. Branner, H. W. Fairbanks, F. E. Matthes, Robert Anderson, G. D. Louderback, and A. S. Eakle, investigated the fault zone in the field throughout its 200 miles of surface ruptures and mapped it from Shelter Cove in Humboldt County to Palm Springs in the Colorado Desert. In this report Lawson (p. 18) named the San Andreas fault, from its rift-valley expression in the San Andreas Lake area of the peninsula, and discussed its features and principal branches. One of the latter, on the southwest face of San Bruno Mountain, he called the San Bruno fault; this he thought converged on the San Andreas fault at a very acute angle, off the Golden Gate, and continued northwestward as the single San Andreas fault zone, through Bolinas and Tomales Bays. On the Atlas map (no. 4), however, only the single San Andreas fault is shown. Incidentally, on this map, the "Haywards fault," in the East Bay, is shown for the first time.

The section of the State Earthquake Investigation Commission report on the *Mechanics of the Earthquake,*

by H. F. Reid, published as volume II in 1910, incorporates significant seismic data, and the Atlas contains seismograms from 67 stations located at various points on the earth. Reid combined conclusions from the seismograph records, field observations of building damage, shearing movements in the fault zone, and especially geodetic measurements, to develop his "elastic rebound theory" to account for the origin of earthquakes. Obvious horizontal shearing movements in the surface rocks along the fault zone led Reid to this now universally held explanation. Modifications of his diagrams appear in nearly all elementary textbooks of geology. It is now known that nearly all destructive earthquakes have been the result of sudden movements of blocks of the earth's crust along faults. Rock, which makes up the material of the earth is elastic and yields to stresses by slow creep over extended periods of time. For example, recent measurements across the San Andreas fault by the U. S. Coast and Geodetic Survey have shown that the block on the east side of the fault is moving southward with respect to the west block at a rate of about 2 inches a year (Whitten, 1955). When the elastic limit of the rock material is exceeded at any piont, or friction along an old fault surface is overcome, an abrupt movement—similar to the 21-foot horizontal displacement which took place along the San Andreas fault to cause the earthquake of 1906—may take place. The fundamental causes of accumulation of such stresses, or the origin of the forces which caused them, are not thoroughly understood, but great faults and earthquakes occur most frequently at the unstable margins of continental platforms and ocean deeps.

In 1914, the U. S. Geological Survey published the San Francisco folio by Lawson. This folio, consisting of 1:62,500-scale colored geologic maps on the 15-minute topographic base, is still the standard reference for geology of the Bay area, although long since out of print. Geologic maps of the Bay area, on a reduced scale, with many revisions of Lawson's work, were recently published by the Division of Mines in Bulletin 154, *Geologic Guidebook of the San Francisco Bay Counties* (Jenkins et al., 1951). On the 1:62,500 San Mateo quadrangle, in Lawson's folio, the San Bruno fault is shown to be buried by alluvium and is not projected into the ocean to the north. However, in the same folio a figure showing fault blocks (Structure, p. 15, fig. 3) shows the San Bruno fault as the major continuous fault extending north into Marin County and the San Andreas merging with it at Bolinas Bay! Recent geologic mapping of the San Bruno area (Bonilla, this volume) leaves unresolved the question of the existence and geologic importance of the San Bruno fault, although most geologists believe it is closely related to the San Andreas.

GEOLOGY OF THE FAULT ZONE

Marin, San Francisco, and San Mateo Counties occupy the central coastal part of the northwest-trending Coast Ranges of California. The most striking topographic and geologic feature of Marin and San Mateo Counties is the San Andreas rift zone which generally bisects the two counties but passes west of San Francisco between the city and the Farallones. In Marin County, the fault separates the Marin peninsula on the east from Point Reyes peninsula on the west. In San Mateo County, the fault zone separates the San Francisco block on the east from the Montara Mountain block on the west. The Golden Gate, transverse to the trend of the central Coast Ranges, represents the mouth of the Sacramento River, drowned by the rise in sea level at the close of the Pleistocene epoch as widespread glaciers of the Ice Age melted.

The Point Reyes-Montara area, or western block, constitutes a region of broadly similar topography and geology. Point Reyes is a triangular peninsula with its very straight eastern edge marked by the rift zone; on the San Francisco peninsula a broad zone involving several related faults of different ages separates the San Francisco block from the Montara block. The Point Reyes-Montara block is an area of low, but locally rugged, relief, underlain by Cretaceous (?) granitic rocks which include fragments of pre-Cretaceous (Paleozoic ?) Sur series gneiss and crystalline limestone. Eroded remnants of Cretaceous (?) Franciscan rocks, Upper Cretaceous, Tertiary, and Quaternary sedimentary rocks remain, overlying and faulted against the older formations. Mount Wittenberg, elevation 1,403, is the highest point on Point Reyes peninsula; North Peak of Montara Mountain has an elevation of 1,898 feet.

The San Francisco-Marin area, or eastern block, includes the area east of the San Andreas fault zone and extending across the Bay to the Hayward fault zone near the western base of the Berkeley Hills. That part of the area west of the Bay is closely involved with the San Andreas fault. The Marin peninsula forms the southern extension of the Mendocino Range. Mount Tamalpais, elevation 2,604 feet, is the highest point on the peninsula and crosses its general trend in a northeasterly direction. The San Francisco block consists of a series of northwest-trending ridges and intermontane valleys; the ridges have gently sloping tops but steep, dissected slopes. San Bruno Mountain, elevation 1,315, and Buri Buri Ridge are the principal summits. Merced Valley lies between these two ridges and opens out to the southeast into San Francisco Bay. The oldest rocks exposed in the San Francisco-Marin block are those of the Cretaceous (?) Franciscan formation; no granitic rocks or members of the Sur series have been found. San Francisco peninsula is the type locality of the Franciscan formation, which was named by Lawson in 1895. The eroded remnants of Upper Cretaceous, Tertiary, and Quaternary sedimentary and volcanic rocks overlie and are faulted against Franciscan units.

Rock Formations and Their Distribution

Franciscan Group. The Franciscan group is a heterogeneous unit of marine sedimentary and volcanic rocks consisting principally of dark sandstone (graywacke), interbedded black shale, a minor amount of limestone, colored radiolarian chert lenses, pillow basalt, and metabasalt or greenstone, all deposited in a marginal marine trough, or geosyncline. The stratified rocks have been intruded by diabase, gabbro, and serpentine of slightly later age. Local metamorphism has produced a group of schists characterized by the blue amphibole, glaucophane. These rocks are often referred to, collectively, as the Franciscan "group." Thickness of the Franciscan group is unknown, as neither top nor bottom have been found in the peninsulas, but exposed beds total more

than 10,000 feet. Red Franciscan chert is well exposed in Golden Gate Park in San Francisco and the varied rocks of the Franciscan group are strikingly exposed in new highway cuts north of Golden Gate Bridge.

In Marin County, Franciscan rocks occur only in the Marin block east of the San Andreas fault and as brecciated rocks and slivers in the fault zone. In San Mateo County, in similar relationship, rocks of the Franciscan group crop out east of the San Andreas fault zone. An area of complexly-faulted Franciscan appears between the San Andreas fault proper and the Pilarcitos fault, a high-angle thrust. The Pilarcitos fault is closely related to the San Andreas and is a major branch of it; locally, the major displacement may have taken place on the Pilarcitos fault prior to Quaternary time. In San Francisco Bay and throughout the Berkeley Hills, East Bay, and northern end of the Diablo Range, Franciscan rocks comprise the basement, the oldest known formation over a very wide area.

Age of the Franciscan group in the Coast Ranges from Santa Barbara County to the Oregon border appears to range from Upper Jurassic to late Lower Cretaceous, although fossil evidence is scant. Study of foraminifers in the limestone beds, pollen, and a few megafossils found on the San Francisco and Marin peninsulas in the last few years gives evidence of late Lower Cretaceous age (Albian stage, on the European scale) of the Franciscan group in the peninsula areas.

Quartz Diorite and Sur Series. The Point Reyes quartz diorite on Point Reyes peninsula west of the San Andreas fault, and Montara quartz diorite west of the San Andreas-Pilarcitos fault zone on the San Francisco peninsula constitute the basement rocks of the western block. They are probably continuous, under all later formations, throughout the western block; similar granitic rocks crop out on the Farallon Islands. The Montara-Point Reyes quartz diorite is deeply weathered in outcrop and is relatively easily eroded. No granitic rocks are known in the East Bay or for many miles north and south of the Bay, east of the San Andreas fault. Here and there in the granitic rocks appear small inclusions or roof pendants of very much older crystalline limestone, schist, and gneiss of the Sur series.

Geologists have long considered the quartz diorite older than the Franciscan group, particularly because no outcrops of granitic rocks intruding the Franciscan have been found, and because the Franciscan sandstone consists largely of granitic detritus. Quartz diorite and the Franciscan group are everywhere in fault contact, and there is no direct evidence that any other type of contact ever existed. However, age determinations (chiefly potassium-argon) by radioactivity of a few specimens of Point Reyes and Montara quartz diorite, made in the last few years, suggest an early Upper Cretaceous age later than the Franciscan (Curtis, Evernden, & Lipson, 1958). If this is true, then we must imagine any Franciscan rocks which were intruded by the quartz diorite in the western block to have been completely removed by erosion down to the granitic core, and that granitic core to lie buried many thousands of feet beneath Franciscan rocks in the eastern block. This situation is most likely to have developed by large movements on the San Andreas fault.

Age of the Sur series is not known, except that the series is older than the intruding quartz diorite. The higher degree of metamorphism of the Sur series rocks, in comparison with the Franciscan, places it certainly as pre-Cretaceous.

Upper Cretaceous. Upper Cretaceous marine sedimentary rocks, unmetamorphosed, fossiliferous, and obviously younger than the Franciscan group and quartz diorite, crop out in scattered areas on both sides of the San Andreas fault in the Bay region. The most common rock types are thin-bedded, alternating sandstone and shale, intensely folded and faulted. Locally, conglomerate beds made up of well-rounded pebbles are present. Upper Cretaceous strata crop out in a belt along the northeast slopes of Montara Mountain, reaching a thickness of about 2,500 feet near San Pedro Point (Darrow, 1951). There, they are unconformably overlain by strata of the Paleocene Martinez formation. No Upper Cretaceous strata have been found in the Point Reyes area.

In the San Francisco-Marin block remnants of Upper Cretaceous formations are known in several places: particularly, just southwest of the Stanford University campus; at Black Point on San Pablo Bay, where the marine Upper Cretaceous is known as the Novato conglomerate; and cropping out extensively in the East Bay in the Berkeley Hills, east of the Hayward fault.

Remnants of Upper Cretaceous formations both east and west of the San Andreas fault show these rocks were once widespread but have been largely removed by erosion; all but small remnants has been eroded from the San Francisco-Marin block.

Although there is abundant organic matter in the Upper Cretaceous rocks, only a few identifiable fossils have been found. However, they leave little doubt of the age. No close correlation of Cretaceous units east and west of the San Andreas fault has been possible.

Paleocene and Eocene. Marine Paleocene strata of the Martinez formation, quite similar to Upper Cretaceous strata, but containing more conglomerate, unconformably overlie Upper Cretaceous beds in a belt on the northeast flank of Montara Mountain.

Marine Eocene sandstone and shale crop out extensively in the Butano anticline west of the San Andreas fault, in southwestern San Mateo County, and in a belt west of Redwood City-Atherton-Stanford in the San Francisco block east of the fault.

No Paleocene or Eocene rocks have been recognized in outcrops in the Marin and Point Reyes peninsulas. From consideration of the regional distribution of the marine rock formations of these ages, it appears likely that Paleocene and early Eocene seas extended barely as far northwest as these areas. A few years ago, a well drilled west of the San Andreas fault near the southern end of the Point Reyes block penetrated marine upper Eocene sandstone at a depth of about 5,000 feet. A thin, very coarse, unfossiliferous, marine conglomerate called the Laird formation (Weaver, 1949), lying on quartz diorite at Point Reyes, below the middle Miocene Monterey formation, may be late Eocene but could also be as young as lower Miocene.

Lower and Middle Miocene. Rocks of the lower Miocene epoch consist largely of shallow-water, coarse sand-

stone, and a minor amount of conglomerate, shale, and thin limestone of the Vaqueros formation, deposited in seas encroaching from the latitude of Half Moon Bay and broadening toward the southeast. The Vaqueros formation has not been found in the Point Reyes-Marin peninsula area (unless the Laird formation be lower Miocene) but crops out extensively in the Montara block south of Montara Mountain and farther south in the Santa Cruz Mountains (Branner, Newsom, and Arnold, 1909). Lower Miocene seas were quite restricted, and the San Francisco, Marin, and Point Reyes blocks were probably slightly above sea level.

Advancing seas, following lower Miocene time, probably covered most of the Bay area in the middle Miocene, including the Berkeley Hills as well as the San Francisco-Marin and Montara-Point Reyes blocks. The marine rocks of middle Miocene age are usually known as the Monterey formation; they consist of thin-bedded siliceous and diatomaceous shale, chert, foraminiferal shale, a small amount of sandstone, and, in some places, a considerable thickness of a variety of extrusive and shallow intrusive volcanic rocks.

Monterey shale covers the larger part of Point Reyes peninsula, lying in broad, gentle folds on quartz diorite. In the northern part of the Point Reyes block, it is about 2,000 feet thick but thickens rapidly southward to about 8,000 feet at Bolinas. In the Montara block, rocks of the Vaqueros formation grade upward into the Monterey formation in southeastern San Mateo County where the formation is characterized by an abundance of flow basalt, intruded diabase, and brecciated limestone. A unit of the Monterey formation (Claremont shale) crops out prominently on the high southwestern slopes of the Berkeley Hills. Rocks of the Monterey formation, which were probably deposited on the San Francisco-Marin block, were long since removed by erosion from that block.

Upper Miocene—Lower Pliocene. The Purisima formation comprises a maximum thickness of 10,000 feet of marine sandstone, mudstone, and diatomaceous and foraminiferal shale, which is petroliferous in the Half Moon Bay-La Honda area. Abundant fossils show that it probably includes rocks of upper Miocene to middle Pliocene age. The formation is very widespread across southern San Mateo County south of Montara Mountain. The upper part of the Purisima formation is very much like part of the lower Merced formation and may be equivalent, in part. Elsewhere in the Montara-Point Reyes block and in the San Francisco-Marin block the Purisima does not appear and probably was not deposited; on the east side of the Bay continental sediments were being deposited at this time.

From early upper Pliocene time to middle Pleistocene, the Bay area, along with most of the rest of California, was involved in a major orogenic epoch. Folding, faulting, uplift, and compression took place to develop the landscape of San Mateo and Marin Counties much as we see it today. One consequence of this orogenic epoch is that all rock formations of the age of the Purisima and older are profoundly folded and faulted; later formations are gently folded, less faulted, and only locally steep-dipping.

Upper Pliocene-Lower Pleistocene. In upper Pliocene and lower Pleistocene time a shallow, narrow seaway developed from the vicinity of Lake Merced southeastward through Merced Valley between the elevated San Bruno and Montara Mountains. Over 5,000 feet of sand, silt, gravel, sandy mudstone, and layers of volcanic ash accumulated to consolidate later as the Merced formation. On the southwestern margin of this trough, and along the rift valley of the San Andreas fault, stream and alluvial-fan gravels, sand, and mud accumulated as the Santa Clara formation, still very little consolidated.

Fossiliferous slightly consolidated rocks of the Merced formation crop out in the San Andreas fault zone from Bolinas Bay for about 5 miles to the north, spreading broadly across more than 50 square miles of northern Marin County, east of the San Andreas fault. In this region, and extending on into Sonoma County, shallow-sea sediments of the Merced formation are, in part, interbedded with a great series of rhyolite, andesite, basalt, tuff, and other volcanic rocks called the Sonoma volcanics. Neither the Sonoma volcanics nor the Merced formation appears to have been deposited on the Montara-Point Reyes block. The Merced and Santa Clara are the oldest formations which were deposited partly in the San Andreas trough.

Late Quaternary. Deposition during late Pleistocene and Recent time is represented by coastal marine terrace deposits, stream terrace deposits, Bay mud, dune sands at Bolinas Bay, Drakes Bay, and the Pacific Ocean north of Point Reyes, alluvium, and thin sediments in the troughs and low spots along the San Andreas rift.

Loosely consolidated arkosic sands, which Weaver (1949) correlated with his late Pleistocene Montezuma formation, crop out in the ridges and troughs within the San Andreas fault zone between Olema and Tomales Bay.

Structural History

Geologic structure of the West Bay area is dominated by the San Andreas fault. Its straight course and obvious topographic and geologic features have marked it for the attention of geologists from its early recognition and study by Lawson and Anderson. A recent summary of the status of our knowledge of the geology of the San Andreas fault, and its relationship to the structural evolution of the Bay area, may be found in the *Geologic guidebook of the San Francisco Bay counties* (Taliaferro 1951). In the same guidebook, a paper by Louderback (1951) discusses the geologic history of San Francisco Bay and the place of the San Andreas and related faults, in development of the late Quaternary structural basin in which the Bay lies.

In spite of the interests of geologists, and the considerable amount of time and attention given by geologists and seismologists to study of the San Andreas fault, it remains very incompletely known and understood. After review of the evidence, it is clear there is no general agreement on satisfactory answers to such fundamental questions as: When did the fault originate? Should the Quaternary and "ancestral" San Andreas be regarded as quite different faults, developed by different stresses, and with entirely different characteristics and displacements? Has the sense and direction of movement (right

PHOTO 1. Aerial oblique view north along the coastline of San Francisco peninsula. The San Andreas fault crosses the coast highway and extends out to sea just north of Mussel Rock (near lower left corner). Westlake Palisades appears on the terrace in upper right center. Mount Tamalpais is profiled at top center. *Official photograph released by United States Navy; taken from altitude 2,000 feet.*

PHOTO 2. Aerial oblique view north across Westlake Palisades (lower left center), Lake Merced, San Francisco, Golden Gate Bridge, and into Marin County. The rift valley of the San Andreas fault, from Bolinas Bay north, can be seen in the upper left corner. *Official photograph released by United States Navy; taken from altitude 2,000 feet.*

PHOTO 3. Aerial oblique view east from the ocean near Mussel Rock (extreme lower right) across Merced Valley, the long ridge of San Bruno Mountain and San Francisco Bay. Mt. Diablo appears on the horizon in the upper left. *Official photograph released by United States Navy; taken from altitude 2,000 feet.*

PHOTO 4. Aerial oblique view south from above Mussel Rock. The sharp cleft of the San Andreas Rift zone runs diagonally across the photograph from lower right to upper left. San Andreas and Crystal Springs Lakes extend southward from the center. Montara Mountain forms the prominence to the right of center. *Official photograph released by United States Navy; taken from altitude 14,000 feet.*

lateral—east block moving south) always been the same, or have great vertical displacements taken place? If dominantly vertical, has the eastern block always moved relatively downward (or upward) or has the direction of movement changed during geologic time? If dominantly right-lateral strike-slip, has the present displacement or strain been at approximately the same rate (about 2 inches a year) since Cretaceous time? Is the cumulative displacement on the fault a matter of several thousand feet or on the order of several hundred miles? What are the relative ages of the granitic rocks which form the basement of the western block, and the Franciscan formation and basic igneous rocks which form the eastern block? To what depth does the faulting extend—5 or 6 miles, or several times this? Is the San Andreas fault becoming more, or less, active? Are historic earthquakes centering in the San Andreas fault zone in the West Bay relieving crustal strain and thus lessening the chances of near-future major earthquakes, or should we say only that they show a continuation of seismic activity associated with the late-Quaternary mountain building of the central Coast Ranges?

The last three questions are largely seismological and some mention of work along these lines will be found in two papers by Tocher in this report; also in *History of earthquakes in the San Francisco Bay area,* by Byerly (1951). Extremes of geological thinking on the San Andreas fault are well represented by two prominent papers, by Taliaferro (1943) and Hill and Dibblee (1953). Taliaferro's conclusions regarding geologic history of the San Andreas fault in the West Bay are restated in the *Geologic guidebook of the San Francisco Bay counties* (1951).

Taliaferro (1943) has said that "the chief difficulty in the way of a study and interpretation of the San Andreas rift is the disentanglement of this line of movement from earlier faults." In geologic mapping, he found that "a profound normal fault developed in the early Eocene along the eastern side of the Gabilan Mesa, by which the southwestern side was elevated with respect to the northeastern side and stripped of its cover of Mesozoic rocks" to expose granitic rocks; on the northeast is a thick section of Franciscan, Cretaceous, and Tertiary sedimentary rocks. This was the "ancestral" San Andreas fault, distinct from the Quaternary San Andreas, and always marks the boundary between crystalline basement complex (granitic rocks and Sur series) and Mesozoic sedimentary rocks (Franciscan and Cretaceous). Taliaferro states further that "the Pilarcitos thrust is not a branch of the San Andreas as has been suggested but is a fault formed first in the Eocene, after the deposition of the Paleocene and before the deposition of the Vaqueros. It is in fact the same Eocene zone of normal faulting which marks the northeast side of the Gabilan Mesa to the southeast." This same fault constitutes the ancestral San Andreas fault in Marin County where it separates the granitic Point Reyes block on the west from Franciscan rocks of the Marin peninsula on the east. Taliaferro (1951) believes "The vertical movement on the ancestral San Andreas fault must have been in excess of 15,000 feet in the central Coast Ranges, decreasing in magnitude in Santa Clara

Photo 5. Aerial oblique view south from Mussel Rock (extending into ocean, lower right). The San Andreas fault probably enters the ocean just north of Mussel Rock and its trace is marked by the sharp defile extending southeastward into the valley of San Andreas Lake which appears in the upper left corner. Sharp Park is the community on the terrace south of Mussel Rock. The dark profile of Montara Mountain is at the extreme top, right. *Official photograph released by United States Navy; taken from altitude 2,000 feet.*

PHOTO 6. Vertical aerial view showing Westlake Palisades in lower right quarter. Mussel Rock projects out to sea about two-thirds of the way up from the lower right corner. From the Rock the diagonal rift valley of the San Andreas fault can be seen extending S. 35° E. *Official photograph released by United States Navy; taken from altitude 14,000 feet.*

Photo 7. Vertical aerial view (south at top) taken above Mussel Rock from an altitude of 2,000 feet. Repeated landsliding and slumping along the sea cliff and along the trace of the San Andreas fault have obscured its exact location. *Official photograph released by United States Navy.*

and San Mateo counties." Taliaferro (1943) has concluded, from extensive field mapping, that there is reasonable evidence that horizontal movement on the San Andreas fault has been less than a mile; the maximum offset of drainage lines "is less than 3,000 feet." Such horizontal shifting is a "very late feature, as it cuts across structures and topography developed in the late Pliocene and Mid-Pleistocene" and the San Andreas fault "has produced no important modification of either the structures or topography formed by the diastrophisms."

Hill and Dibblee (1953) have expressed fundamentally different views from those of Taliaferro on the geologic history of the San Andreas fault. Again, their conclusions are based on geologic mapping; in fact, Dibblee has personally mapped over 300 miles along the San Andreas fault zone. They believe "that (1) the San Andreas is a steep fault zone of variable width consisting of one or several nearly parallel faults; (2) its inception was quite likely pre-Tertiary, and it is now active; (3) it has probably been characterized by right lateral displacements throughout its history; (4) it marks such an important contact that rarely can it be crossed, except in Recent alluvium, without passing into significantly different rocks; and (5) its cumulative displacements of some rock units is at least tens of miles, and older rocks may have been displaced a few hundred miles." In the same paper in a figure, and in the text, these authors indicate a right lateral displacement of approximately 10 miles since Pleistocene deposition (in the San Emigdio Mountains—Temblor Range area) about 65 miles since upper Miocene time, possibly 175 miles since early Miocene, 320 miles since the Cretaceous, and perhaps 350 miles since Jurassic time. Hill and Dibblee consider that "in many places the San Andreas is a wide zone comprising several important faults which are parallel or nearly parallel to the recent trace," and that "the apparent dip-slip displacements are mainly the result of substantial lateral movements which put unlike geologic sections in juxtaposition."

Quaternary Faulting and Geologic Features of the 1906 Earthquake

The prominent topographic and geologic features of the San Andreas fault zone in Marin and San Mateo Counties make it evident at once that the fault is certainly a major structural feature of late Quaternary time. Unraveling of its pre-Quaternary history is much more difficult and uncertainties multiply as we attempt to trace its movements back into early Tertiary time and to document a possible pre-Tertiary history.

Across Marin County, from Bodega Bay to Bolinas Bay, the fault follows a remarkably straight course, S. 34° E., in a linear depression marked by the features of a classic rift valley. Most prominent is the long, narrow, shallow, Tomales Bay—a mile wide and 15 miles long. South of that bay, the rift zone is a steep-sided trough, as deep as 1,500 feet, with its lower levels characterized by a most remarkable succession of minor, alternating ridges and gullies parallel to the general trend of the fault zone. Surfaces of the ridges and gullies are spotted by irregular hummocks and hollows. Many of the hollows are not drained and fill with water seasonally to form the sag ponds so common here and elsewhere along the San Andreas rift. Drainage of the rift valley is by two creeks running within and parallel to the rift: one northward into Tomales Bay and the other southward to Bolinas Bay. Each trunk creek is fed by innumerable small tributaries entering at right angles. Geologically Recent adjustment of the drainage in the rift zone leaves little evidence to indicate direction and sense of relative movement on the San Andreas fault (Lawson, 1908, vol. I, p. 31, fig. 2). The difference in rock formations on the two sides of the rift in Marin County is very striking: granitic rocks of the Point Reyes peninsula on the west, and Franciscan rocks of the Marin peninsula on the east. Within the fault zone (rift valley) is a disorganized jumble of fault-brecciated rocks of both the eastern and western blocks; the result of hundreds of repeated ruptures on different fault planes within the San Andreas fault zone in late Quaternary time. Features of the rift valley have resulted from (1) repeated, discontinuous fault ruptures on the surface, often with the development of minor depressions or graben; (2) landsliding, triggered by earthquake waves and surface faulting; and (3) erosion of brecciated, readily weathered rock. North of Bolinas Bay fossiliferous sedimentary rocks of the Plio-Pleistocene Merced formation crop out on both sides of the fault with questionable offset. Thus, the rift valley topography as seen today has been developed in upper Pleistocene and Recent time, but the total displacement on the fault during this time need not have been great. Faulting prior to deposition of the Merced formation, however, must have been of far greater magnitude.

Across San Mateo County, from the vicinity of Mussel Rock toward the southeast, the San Andreas fault zone follows the same trend as in Marin County, but is somewhat less straight and is complicated by several subparallel faults. All the rift-valley features of Marin County are repeated in San Mateo County. Near Mussel Rock are great landslides, obscuring the fault trace, and for a few miles to the southeast is a succession of sag ponds, notched ridges, and rift-valley lakes within a deeply trenched valley which forms a striking feature as seen from the air. The long, narrow San Andreas Lake and Crystal Springs Lakes are natural lakes which were enlarged by artificial dams built many years ago. In San Mateo County the rift lies wholly within Franciscan basement rocks and the boundary between these and the western block of granite rocks is the Pilarcitos fault. The Plio-Pleistocene marine Merced formation near Mussel Rock and its probable land-laid equivalent to the southeast—the Santa Clara formation—crop out on both sides of the San Andreas fault and have been offset by it. Unfortunately, the fault so closely coincides with the trend of the narrow basin of deposition of the Merced and Santa Clara formations that, as in Marin County, we cannot be sure of the amount and nature of late Quaternary movement on the fault. The rift-valley topographic features are clearly younger than the Merced formation.

The San Andreas fault had been recognized and mapped prior to 1906 (Lawson, 1893 and 1895; Anderson, 1899), but surface ruptures along the fault trace occurring on April 18, 1906, coincident with the greatest earthquake recorded in California, furnished a wealth of data for study by geologists and seismologists. Open

Photo 8. Earth ruptures which represent the surface expression of faulting on the San Andreas fault which caused the San Francisco earthquake of 1906. Photo looking north from a point at the south end of Tomales Bay, northwest of Olema, taken shortly after the great earthquake of April 18. *From the J. C. Branner collection, Stanford University.*

Photo 9. Photograph from the same point as Photo 8 taken in April 1958, showing the effects of erosion and deposition in the rupture zone in 50 years. In the past 3 or 4 years a small gully has been eroded headward exposing the steeply east-dipping fault plane of 1906. The light-colored material on the left is the late Quaternary Montezuma formation of Weaver; black soil has slumped downhill from the right to fill in the ruptured zone against the fault plane. *Photo from a kodachrome.*

breaks in the ground surface were photographed, studied, mapped, and described in great detail in the two-volume report and Atlas of the State Earthquake Investigation Commission (Lawson, and others, vol. I, 1908; Reid, vol. II, 1910). Many of the observations made at that time are of great significance in understanding the origin and development of rift valleys and the nature of the San Andreas fault: (1) Open ruptures were mapped along the fault trace on the land from San Juan Bautista in San Benito County to Telegraph Hill north of Shelter Cove, in Humboldt County; (2) Individual fault ruptures were not continuous, but extended for a few feet or a mile or more, with the movement then picked up along en echelon breaks; (3) The ruptures were often complex, frequently with small grabens developed between two breaks; (4) The greatest component of displacement, measured by offset fences, roads, and other structures, was horizontal, right-lateral, with a maximum 14-16 feet on the San Francisco peninsula and 21 feet at the south end of Tomales Bay; (5) The true vertical component was difficult to measure, because of soil slumping and topography, but probably was a maximum of 3 feet, with the western block relatively up; (6) The amount of apparent displacement varied irregularly along the fault trace but, in general, decreased in both directions from the maximum at the south end of Tomales Bay.

A succession of earthquakes, probably originating in the San Andreas fault zone, has occurred since 1906, but no surface ruptures have been found (Byerly, 1951; Tocher, this volume). Until the San Francisco earthquake of March 1957, seismologists have not been able to obtain many data on the fault plane and nature of faulting. However, Tocher (this report) was able to calculate, from seismic wave data, that movement causing that earthquake was probably on a near-vertical plane in the San Andreas fault zone, at shallow depth, had a predominantly vertical component, and that the east block was probably displaced relatively upward. Resurveys since 1906 of the first-order triangulation network by the U. S. Coast and Geodetic Survey suggest that strain or displacement on the San Andreas fault has averaged about 2 inches a year, the east block moving relatively south (Whitten, 1949, 1955, and this report).

Perhaps increments of displacement on the San Andreas fault in the West Bay have been predominantly horizontal at one time and predominantly vertical at another; there is even some possibility that vertical components may locally be opposite at different times.

Pre-Quaternary Faulting

In considering the nature of pre-Quaternary faulting we must reason without the useful tools of geomorphology, seismology, and geodesy, turning instead to reconstruction of geologic history from the record in the rock formations.

Remnants of the oldest rocks of the West Bay—the Sur series—caught up in the Cretaceous granitic rocks of the Montara-Point Reyes block show only that pre-Cretaceous mountain building occurred but give no direct evidence of ancient faulting. Rocks of the Franciscan formations, which doubtless once covered the entire Bay area, plus the basic intrusions and flows, which together constitute the Franciscan group, are

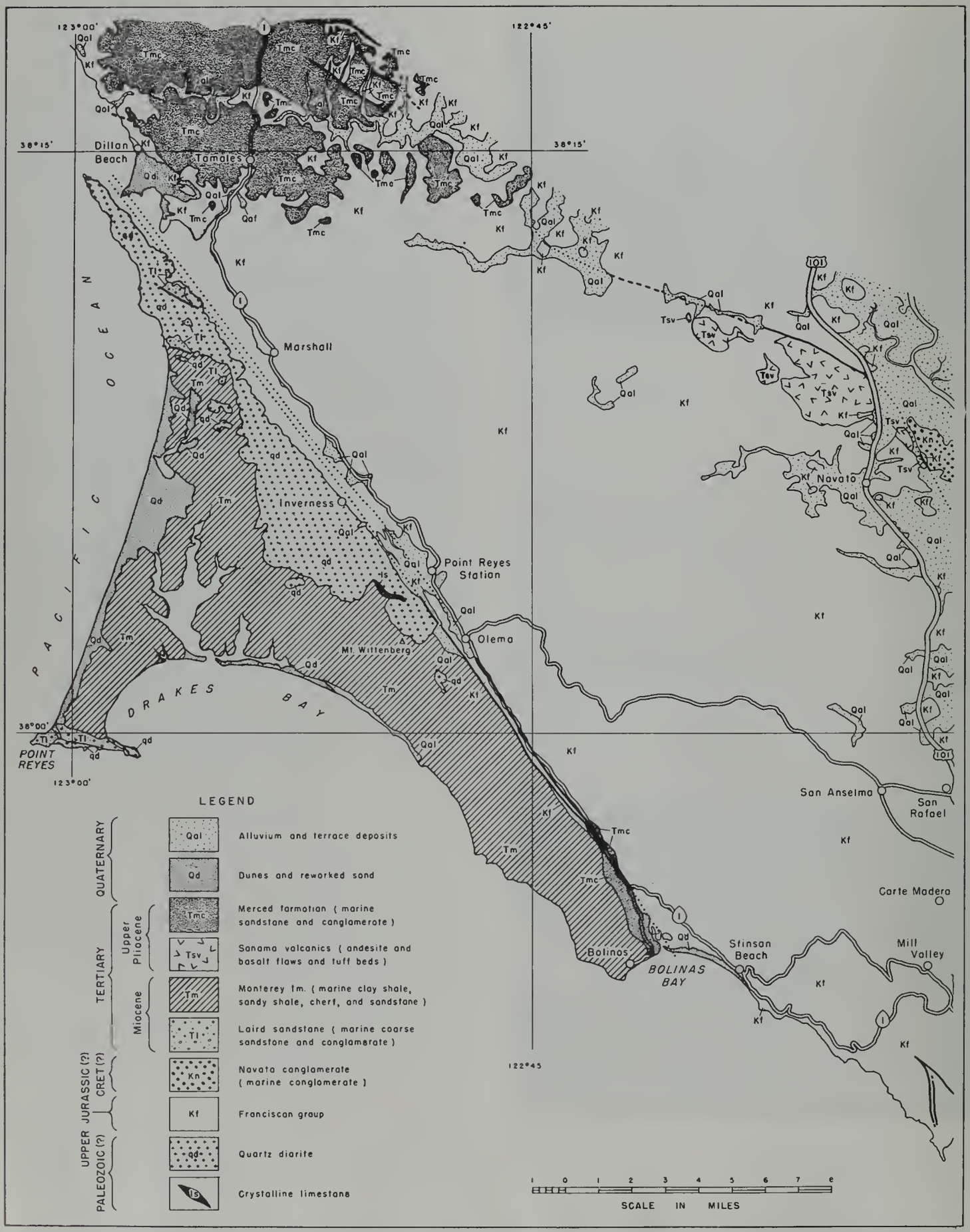

FIGURE 2. Geologic map of San Andreas fault zone in Marin County. *Modified from Plate 4, California Journal of Mines and Geology, vol. 51, no. 3.*

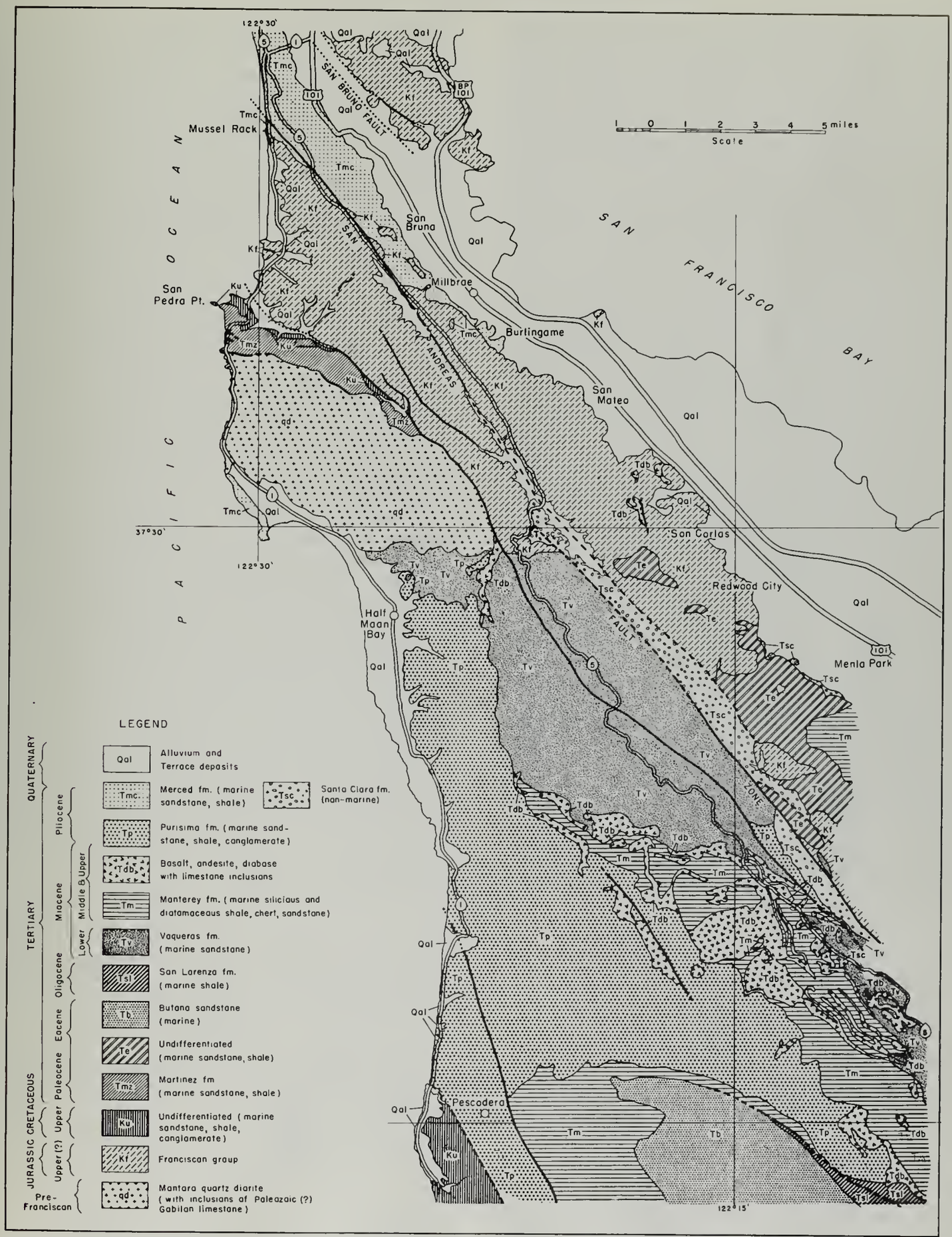

FIGURE 3. Geologic map of San Andreas fault zone in San Mateo County. *Modified from plate 5, California Journal of Mines and Geology, vol. 51, no. 4.*

rather broadly folded into open synclines and anticlines, but these structures are complicated by innumerable tight minor folds, by the difference in competence of massive sandstones and thin-bedded shales, and by faulting. Present status of geologic knowledge does not show, with certainty, whether the granitic rocks are slightly older or slightly younger than the Franciscan; both are mid-Cretaceous or early Upper Cretaceous. In any case, contact between these two major units of basement rocks is always a profound fault. This contact fault on the San Francisco peninsula is the Pilarcitos "thrust" whereas on the Marin peninsula the contact fault coincides with the San Andreas fault.

Fortunately, a wedge of sedimentary rocks of critical importance has been preserved in the complex San Pedro syncline between a faulted contact with Montara granodiorite on the south and the Pilarcitos fault on the northeast (Darrow, 1951). The syncline includes marine sedimentary rocks of post-Franciscan, Upper Cretaceous age which are unconformably overlain by marine Paleocene strata. Basement is the granodiorite. Since the Pilarcitos fault has cut out Paleocene strata which were once deposited widely over the Bay area, it is post-Paleocene in age. This relationship is clearly shown on the accompanying geologic map of San Mateo County. That map also shows that, a few miles to the southeast, a southward continuation of the Pilarcitos fault seems not to have offset the lower Miocene Vaqueros formation. At Pilarcitos Lake, the fault dips 40° NE and seems to be a thrust; its southward continuation lies within the Vaqueros formation, is straighter, more nearly vertical, and may merge with the San Andreas fault in Santa Clara County. Thus, major faulting, of large displacement, took place between Paleocene and lower Miocene time to bring granitic rocks into fault contact with the Franciscan. It is suggested that the Pilarcitos fault was not developed as a thrust but has been subsequently folded in the San Pedro syncline segment. The same contact—granitic rocks on the west faulted against Franciscan rocks on the east—coincides with the San Andreas fault on the Marin peninsula. The Pilarcitos fault appears to turn northward at the mouth of San Pedro Valley and may well continue below sea level to Bolinas Bay. Earliest definite geologic evidence of an "ancestral San Andreas fault" (if we care to use that term) in San Mateo and Marin Counties is thus represented by the granite-Franciscan contact fault developed between Paleocene and early Miocene time. Whether this fault was predominantly dip-slip or strike-slip seems undeterminable in the West Bay area. Franciscan rocks, which once overlay the granitic rocks, were being removed by erosion during Paleocene time and probably had been largely removed from the Montara Mountain-Point Reyes block before upper Eocene time, for marine upper Eocene rocks (Butano sandstone) lie directly on granite in southern San Mateo County and in the southern part of Point Reyes peninsula. Eocene rocks lie directly on Franciscan in the San Francisco block. This is evidence in support of relative uplift of the western granitic block on the "ancestral San Andreas fault" in early Eocene time. There was probably uplift and erosion of the Bay area after the close of Eocene time, for Oligocene formations are missing in the Bay and peninsula areas, except in the Santa Cruz Mountains in southeastern San Mateo County and Santa Cruz County.

Lower Miocene seas advanced across the ancestral San Andreas fault zone and had spread widely over the entire Bay area by middle and early upper Miocene time. Such a statement can be made, in spite of the absence of the middle to upper Miocene rocks of the Monterey formation on the San Francisco-Marin block, because the nearest fine-grained sedimentary rocks adjacent to that block on its eastern and western margins show no evidences of shoreline facies. Thus, the fault was probably relatively inactive during the Miocene epoch. Early and mid-Miocene volcanism, particularly in San Mateo County, is evidence that some crustal instability persisted for a time. Siliceous and diatomaceous shale, chert, and a minor amount of limestone, siltstone, and sandstone of the late middle and upper Miocene Monterey formation show the widespread seas, lack of any high-standing marginal lands, and stability of the entire West Bay area at that time. Latest sediments of the Miocene epoch were much coarser (San Pablo group), were deposited in restricted arms of the seas in the East Bay, and give evidence of uplift and increasing crustal unrest at the close of the epoch.

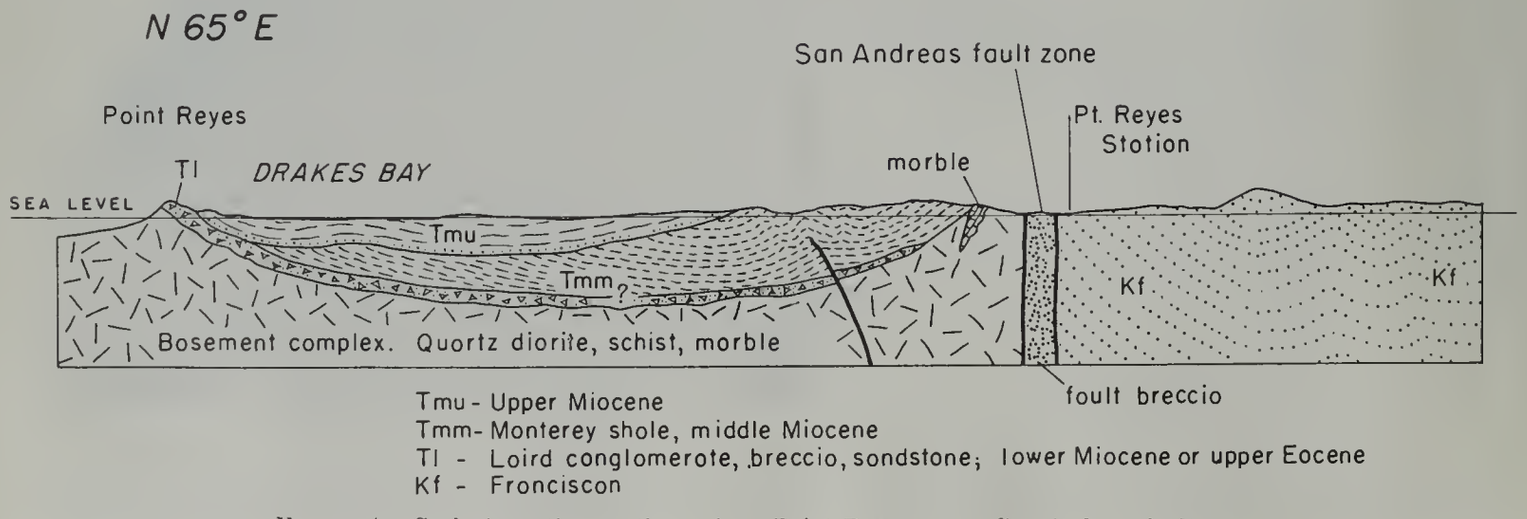

FIGURE 4. Geologic section northeast from Point Reyes across San Andreas fault zone.

Beginning in late Miocene time, the San Francisco and Marin blocks were elevated to form a mountainous ridge that existed through the lower Pliocene; from it all the rocks of the Monterey formation were removed. The Monterey formation west of the San Andreas fault was mildly folded and faulted but was preserved on the low-lying and rigid granitic basement of Montara and Point Reyes. Doubtless the ancestral San Andreas fault still formed the structural boundary between the eastern (Franciscan) and western (granitic) blocks, but movement of the eastern block must have been relatively upward—whereas in the profound fault movements during post-Paleocene to pre-Miocene time, the western block moved relatively upward!

The apparent reversal of great displacements on the ancestral San Andreas fault, in the two intervals of its greatest activity just described, leaves geologists with a choice of several possible explanations: the two great movements were primarily vertical and were, in fact, reversed; or, the major component of displacement was horizontal and the two different geologic provinces of the eastern and western blocks were brought into juxtaposition by great right lateral movements, like those on the modern San Andreas fault in 1906; or at one major period of activity (the older?) the vertical component of displacement was dominant, while at another time the horizontal predominated.

All three explanations are geologic possibilities and none may be ruled out of consideration. If the first is basically correct, then characteristics of the great fault zone and the forces which developed it must have changed profoundly at different orogenic periods in geologic history. At least, great uplift of the western block to allow removal of many thousands of feet of Franciscan, Upper Cretaceous, and Paleocene rocks by erosion, and then, later, great uplift of the eastern block to accomplish removal of the Monterey rocks would account for the geologic facts. Whether such large reversals of movement have occurred on similar great faults, geologists have not yet proved beyond reasonable doubt. However, attention was called, earlier in this paper, to a small upward component of movement of the western block of the San Andreas fault in 1906 and to seismic evidence for probable upward movement of the eastern block in 1957.

The second alternative—that movement on the San Andreas fault, ancestral and modern, has always been predominantly horizontal—is a geologically attractive explanation. In the first place, it is consistent with known modern movements, particularly those of 1906. It requires no reversals of forces and nature of movements in geologic time; contrasting rock units could all have been brought into their present relationships by right lateral displacement, since mid-Cretaceous time, of something on the order of modern known displacements, if cumulative to many miles. Rock formations of increasing geologic age in the two opposite fault blocks show greater and greater right lateral offset, if a little imagination is used in matching them! Unfortunately, matching of geologic units of different ages across the fault is not clear enough to be wholly convincing to those who would not agree with large lateral displacement.

The third suggested explanation—that displacement on the great fault may have been predominantly vertical at one time and horizontal at another—also fits the geological facts. It may well be that a great ancestral San Andreas fault developed (with its largest displacements in early Eocene time) with thousands of feet of uplift of the western block to account for removal by erosion of Franciscan and Upper Cretaceous strata, leaving granitic rocks exposed, while the eastern block was relatively downdropped, thus preserving formations of those ages. Perhaps the apparent reversal of this vertical movement, which closed the Miocene epoch and caused the Monterey formation to be stripped from the eastern block, initiated a new regime in which displacement, in reality, became right-lateral strike-slip.

The greatest period of Coast Ranges diastrophism in which the West Bay was involved extended from early

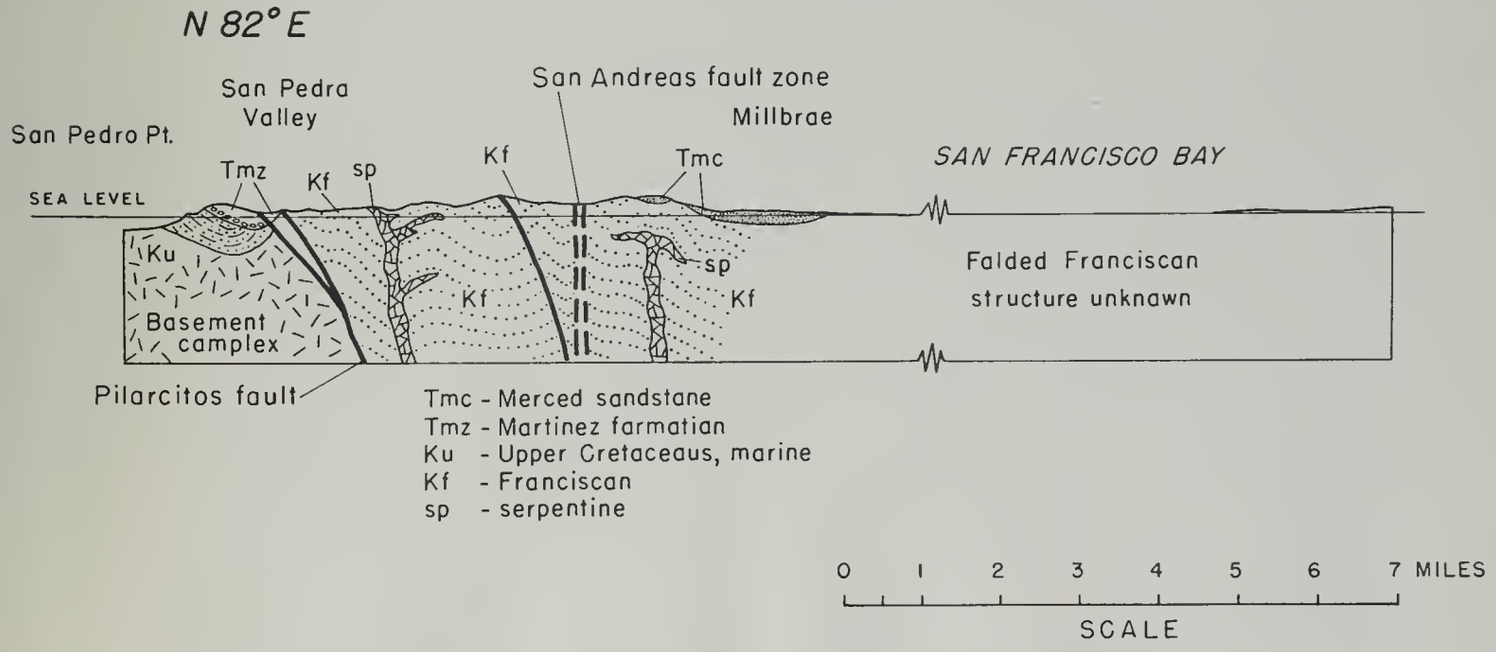

Figure 5. Geologic section northeast from San Pedro Point across San Andreas fault zone.

upper Pliocene to mid-Pleistocene time. Acute folding, faulting, and mountain-building took place, and the north-northwest trend of the present Coast Ranges developed. Local basins between the ridges received coarse-grained sediments, mostly land-laid; but a narrow, marine trough, receiving sediments of the Merced formation, developed along and east of the San Andreas fault zone from the vicinity of Burlingame in San Mateo County northwest across Bolinas Bay to spread widely as a very shallow sea in northern Marin and Sonoma Counties. This trough reached its greatest depth by subsidence near Lake Merced. There is little doubt that the Merced trough, at least in the Lake Merced-Bolinas Bay segment, was controlled by the San Andreas rift zone. Early upper Pliocene time thus initiated development of the modern topographic, drainage, and geologic features of the West Bay, as well as the depression in which the Bay lies. The history of the San Andreas fault proper, as seen today, began at this time. Because of the dominant, prevailing north-northwest trend of structural and topographic features, of which the San Andreas fault zone partakes, it is difficult to analyze post-Merced, pre-1906 movements on the fault—but they need not have been large. It is clear that there have been repeated movements on near-vertical fault planes within the fault zone, cutting the Merced formation and continuing to the present day. The sense and amount of these movements is less clear.

GEOLOGIC OBSERVATIONS IN THE EPICENTRAL AREA OF THE SAN FRANCISCO EARTHQUAKE OF MARCH 22, 1957

By M. G. Bonilla
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ABSTRACT

The most concentrated damage to buildings in the San Francisco earthquake of March 22, 1957, occurred in part of the Westlake subdivision, hereafter referred to as Westlake. Westlake is underlain by soft sediments ranging in age from Pliocene to Recent. Former canyons in Westlake now contain artificial fill that is almost 70 feet thick in places. Dips in the Merced formation of Pliocene and Pleistocene(?) age in Westlake are to the northeast and range from 10 to 80 degrees. The San Andreas fault is about 0.8 mile south of Westlake; evidence for other faults closer to Westlake is inconclusive. No evidence of new surface movement was visible on any of these faults. Landslides occurred principally along the sea cliffs and along the shores of Lake Merced; those along the sea cliffs were mostly sand runs in dry sand and those along Lake Merced probably were sand flows caused by spontaneous liquefaction of saturated sand fill. Westlake Palisades had more structural damage than the rest of Westlake. The reason for this is not clear but it may be related to the proximity of a sea cliff. In Westlake Palisades, houses on compacted artificial fill were generally less damaged than those on natural ground. Within the areas of natural ground, there was no clear relationship between damage and foundation material.

INTRODUCTION

The area under discussion lies chiefly in the northwest corner of San Mateo County but also includes part of the city of San Francisco (fig. 1). Westlake is a housing subdivision that covers an irregular area in the northwest corner of San Mateo County. Most of the damage to buildings was concentrated in the part of Westlake that is included in the geologic map (fig. 2). Although the geologic map includes only part of Westlake and a small area that is not part of Westlake, the area of figure 2 will be referred to in this paper simply as Westlake. The portion of Westlake bounded by Skyline Boulevard, the coast highway, and Westmoor Avenue is called Westlake Palisades. Beyond the limits of Westlake, Westmoor Avenue is called Edgemar Road (fig. 1).

The original topography in Westlake was a hilly surface that generally decreased in altitude to the east and to the north. The surface was bounded on the west by a

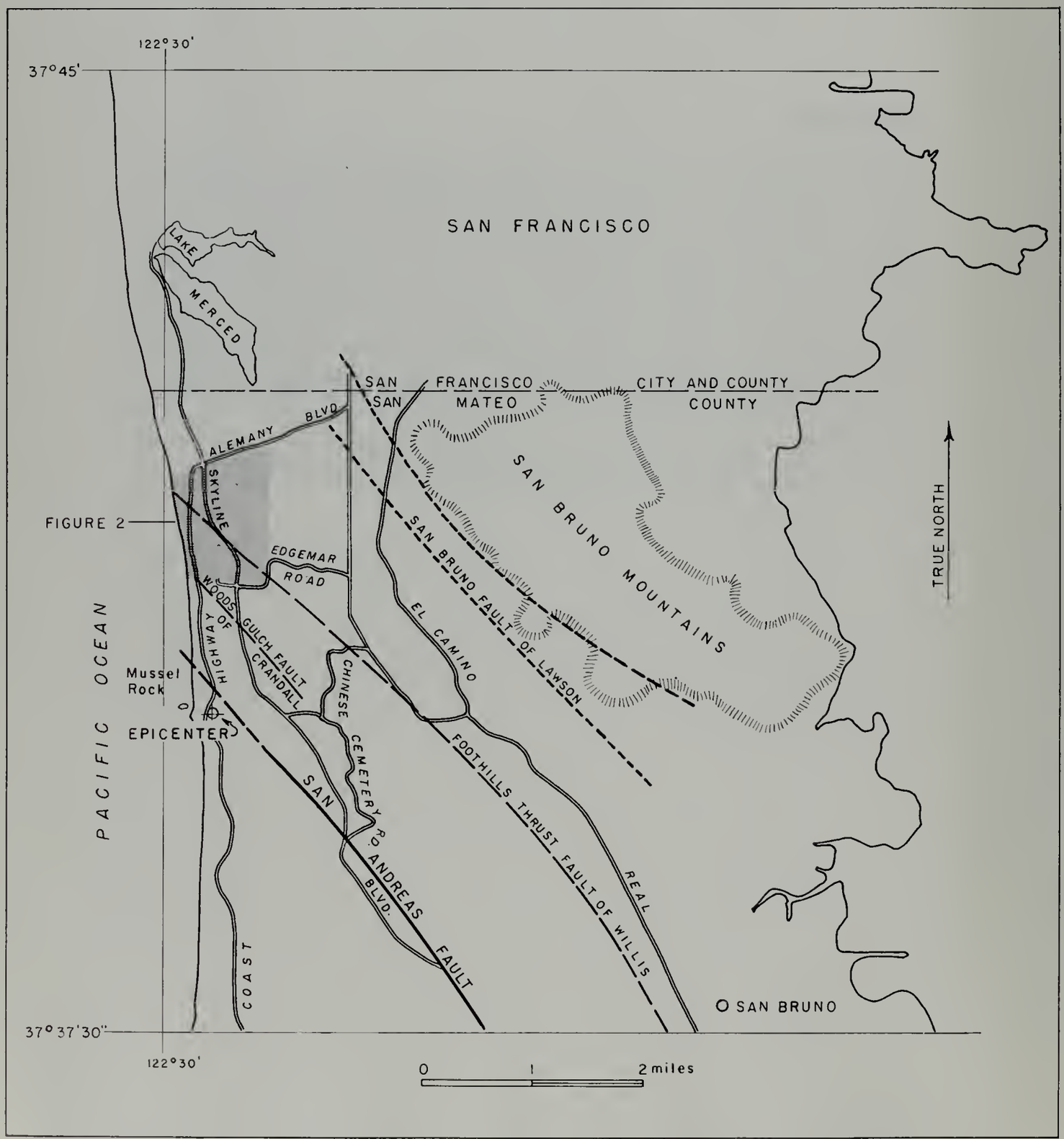

FIGURE 1. Index map showing faults in epicentral area. Shading shows area covered in figure 2.

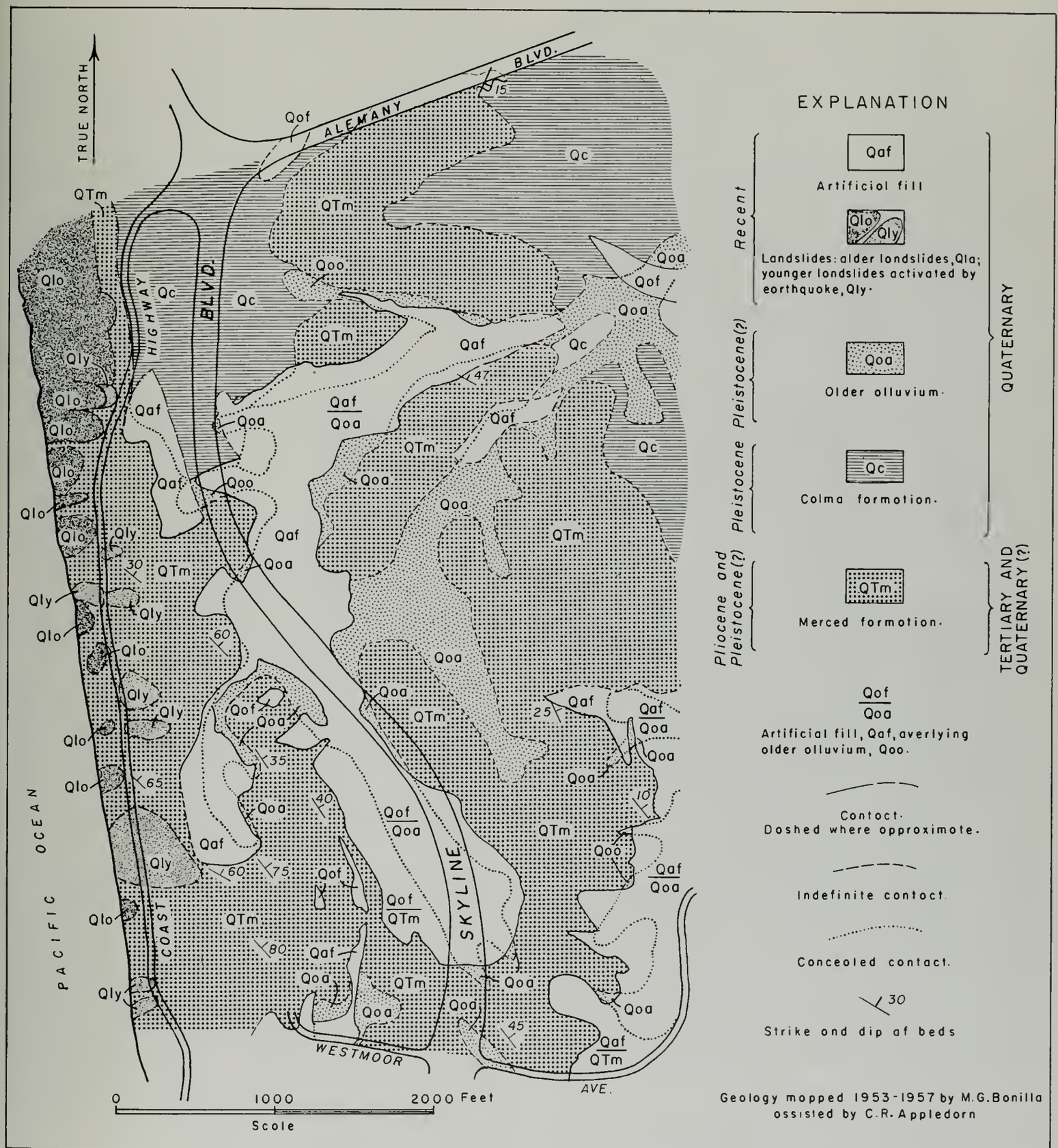

FIGURE 2. Geologic map of Westlake area, Daly City.

sea cliff, and it was traversed by small canyons reaching a maximum depth of about 100 feet. During grading operations for the housing development, the hilltops were removed and the material was placed in the canyons so that the present relief is considerably less than the original relief. Westlake is bounded on the west by a sea cliff that has a maximum altitude of about 500 feet.

The field work on which most of this paper is based was done prior to the earthquake as part of a geologic mapping project which includes the San Francisco South quadrangle. The mapping was done by surface methods, such as examining outcrops and excavations, and plotting the field data on aerial photos and large-scale topographic maps. Field observations were supplemented by stereoscopic study of aerial photographs and the study of test borings supplied by various agencies. Field work was done intermittently from 1953 to 1957. During 1954 and 1955, Conrad R. Appledorn assisted the writer in the geologic mapping.

The writer wishes to acknowledge the fine cooperation received from Henry Doelger, Builder, Inc., the developers of Westlake; Theodore V. Tronoff, Civil Engineer; and Woodward, Clyde and Associates, the engineering firm that did the soil testing in Westlake.

Publication of this report has been authorized by the Director, U. S. Geological Survey.

GEOLOGY

Hard rocks of the Franciscan group crop out south and east of Westlake but not in Westlake itself, where the hard rocks are probably half a mile below the surface. Soft rocks of the Merced and Colma formations underlie most of Westlake. Older alluvium forms terraces near the bottoms of the canyons and Recent alluvium forms small deposits along the stream beds and behind artificial barriers such as highway and railroad fills. Beach sands lie at the foot of the sea cliffs, and large landslide deposits are along the cliffs. The Recent alluvium and beach sand are not shown on the geologic map.

Results of tests made by Woodward, Clyde and Associates during the investigation of foundation conditions in Westlake are listed in table 1 according to formation. The assignment of the samples to specific formations was made by the writer on the basis of lithology and location of the sample with regard to geologic boundaries. Samples were included in the table only when assignment to a particular formation was reasonably certain. The term "loam" in table 1 is taken from the logs of test borings, where it was used to describe friable fine-grained material such as clayey silt or clayey fine sand.

Table 1. Soil test data, Westlake area.

Material		Penetration resistance, blows per ft.*	Moisture content, percent of dry weight	Dry density, lbs. per cu. ft.	Unconfined compressive strength, lbs. per sq. ft.
ARTIFICIAL FILL:					
Sand	Average	17	12	109	2780
	Range	7–24	11–14	103–117	290–6830
	No. of samples	7	7	7	4
Loam**	Average	13	24	98	5148
	Range	7–17	18–33	84–109	2340–8540
	No. of samples	6	6	6	6
Clay	Average	15	32	90	4980
	No. of samples	1	1	1	1
OLDER ALLUVIUM:					
Sand	Average	14	17	108	4327
	Range	8–20	7–26	97–116	1710–9370
	No. of samples	9	9	9	6
Loam	Average	14	19	99	4260
	Range	6–28	12–28	87–117	1220–7520
	No. of samples	8	7	7	7
Clay	Average	14	25	103	3270
	Range	10–20	13–42	78–115	980–6000
	No. of samples	3	3	3	3
COLMA FORMATION:					
Sand	Average	28	13	108	880
	Range	8–48	10–17	107–109	540–1220
	No. of samples	3	3	3	3
Loam	Average	18	17	110	680
	No. of samples	1	1	1	1
MERCED FORMATION:					
Sand	Average	27	14	104	2006
	Range	5–48	8–28	93–129	390–4340
	No. of samples	17	17	17	11
Loam	Average	18	30	92	6540
	Range	16–21	27–33	88–95	5660–7420
	No. of samples	2	2	2	2
Silt and Clay	Average	30	34	88	5724
	Range	4–84	20–54	67–102	730–10200
	No. of samples	14	14	14	14

* Weight of 140 lbs. dropping 30 inches, driving 2-inch modified California sampler.
** Friable fine-grained material such as clayey silt or clayey fine sand.

Stratigraphy

Merced Formation, General. The Merced formation crops out in a belt that crosses the San Francisco peninsula diagonally from Lake Merced to a point about 4 miles southeast of San Bruno (fig. 1). The belt is widest along the Pacific Ocean side where it reaches from Lake Merced to Mussel Rock and narrows gradually toward the southeast. The Merced formation along the beach is about 5,000 feet thick. It overlies the Franciscan group unconformably and is unconformably overlain by the Colma formation. The Merced formation is principally silt, clay, and fine sand, and contains a few lenses of gravel. The silt, clay, and sand commonly are not indurated so would not be considered rock by the layman. Some of the gravel, particularly where it has fossils, is firmly cemented to hard rock. The gravel beds are generally less than a foot thick. In places the silt and clay are indurated to the extent that they are difficult to excavate with light power tools such as trenching machines. The sand in the Merced formation is medium gray where fresh and yellowish-gray to yellowish-orange where weathered. The silt and clay are medium or dark gray where fresh, and yellowish-orange, light gray, or grayish-orange where weathered.

Stratification in the Merced is moderately distinct in most places and is emphasized by differences in grain size, by color banding, resistant beds, fossil-bearing beds, or thin beds of clay, lignite, gravel, or volcanic ash. Many of the strata pinch out within a few hundred feet and some strata, such as thin gravels, pinch out in a few tens of feet. These variations make correlation of strata in distant outcrops difficult and uncertain.

Stratification in the sand varies considerably, ranging from finely laminated * to very thickly bedded. Locally the sand is cross-stratified, particularly where gravel is present, and in places the laminae are contorted. Thicknesses of the sand strata range from a fraction of an inch to 30-foot zones that appear to be structureless. Most strata in the sand units of the Merced are less than 1 foot thick. In a few places the sand has a false stratification due to color banding which may be at any angle to the true stratification.

The silt and clay are evenly laminated and locally cross-laminated. In many places, however, particularly in either the thicker units of silt or where the silt is weathered, the stratification is indistinct or not visible. In places the stratification is made visible by thin discontinuous cemented zones, by fossil beds, by shaly partings, or by thin beds of lignite.

Merced Formation, Westlake Area. The Merced formation within the area of figure 2, where it has a larger proportion of sand than the formation as a whole, is approximately two-thirds sand and one-third silt and clay. The sand, for the most part, is clean, well sorted, medium grained, subangular to subrounded, and made up chiefly of fresh quartz and feldspar with a minor amount of mica and dark heavy minerals, chiefly magnetite. The sand is permeable except where it is silty. The sand is almost everywhere uncemented, friable, and is easily excavated. A few thin discontinuous beds are cemented, commonly with calcium carbonate. These cemented zones are associated with fossils in most places. Within the sand, and in places within the silt and clay, are a few lenticular strata of rounded pebble-gravel that contain a sandy matrix. Some of these strata, particularly where they are fossiliferous, are cemented to form a hard rock. Most of the pebbles are moderately weathered but they range from fresh to extremely weathered. The pebbles are chiefly sandstone of the Franciscan group with lesser amounts of chert of the Franciscan group, pre-Franciscan chert, chert of the Monterey group, small amounts of granitic rock, volcanic rocks, and waterworn shell fragments. Zones of silt and clay are interlayered with the sand. The thickness of the silt and clay zones ranges from about 50 to 200 feet. Most of the silt and clay zones have a high dry strength, but in places they are friable. At natural moisture content they are very stiff, having an average unconfined compressive strength of almost 2.9 tons per square foot (table 1). In places the silt and clay are almost a shale and are difficult to excavate with light power tools such as trenching machines. They are noncalcareous except in or adjacent to fossil-bearing zones. The silt and clay are relatively impermeable compared to the sand, so that ground water tends to travel in the sand at the contact with the silt and clay. Many artificial cuts have developed springs and seeps at these contacts. Within the sand there are a few clay zones 20 feet thick or less. Most of the clay in these thin zones is tough and moderately plastic or very plastic. Some of the clay is hard and shale-like and contains gypsum and calcareous cement; a few clay beds swell markedly when wetted.

During grading operations for the housing tract a bed of friable volcanic ash about a foot thick was uncovered near the intersection of Westmoor Avenue and Skyline Boulevard. The ash, exposed intermittently for 2,500 feet northwest of the intersection, is clean, white, fresh to moderately weathered, and is made up mostly of sharp fragments of volcanic glass, with very rare diatom fragments. This ash is tentatively correlated with the ash that crops out in the sea cliff west of Lake Merced. During grading operations another ash bed was also exposed, at the point in the northeast part of figure 2 where a dip of 47 degrees is shown. This ash bed is about 6 feet thick and probably is the same zone as the ash and diatomaceous earth zone that crops out along Edgemar Road about 0.4 mile west of Junipero Serra Boulevard (fig. 1), and is also probably equivalent to the thick volcanic ash that crops out southwest of Lake Merced and which was mined for use as an abrasive prior to 1923.

The Merced formation is considered by most paleontologists to be Pliocene and Pleistocene(?) in age. The upper part of the formation has been tentatively correlated with the Alameda formation of Pleistocene age on the basis of an ash bed found in a drill hole in San Francisco Bay (Louderback, 1951, p. 87). Although the ash beds in the Merced are mineralogically similar to the ash found in the bay, the refractive indices of the volcanic glass are different. Of ash samples from 10 localities in the Merced formation in the Lake Merced-Westlake area, the glass in nearly all of them had an index of 1.50, and the maximum index was 1.51. The refractive index of the glass in the bay ash sample is 1.52, according to Max D. Crittenden Jr. (Trask and Rolston, 1951, p. 1083). Because of this, the writer considers the correlation of the upper part of the Merced formation with the Alameda formation as rather questionable.

Colma Formation. The Colma formation of Pleistocene age (Schlocker, Bonilla, and Radbruch, in press) crops out principally in the valley that extends from Lake Merced to San Bruno. It lies unconformably on the Franciscan group and the Merced formation, and is uncomformably overlain by alluvium, dune sand, and perhaps by bay mud. The greatest thickness of sediments of the Colma seen in a single outcrop is about 75 feet; the total thickness of the formation is not known, but it may be as much as 200 feet. The Colma formation is chiefly friable sand, and in most outcrops is pale to dark yellowish-orange. In a few places it is brown, and where it is not weathered the color ranges from yellow-gray to light or even dark gray.

Typically the Colma formation is horizontally stratified and cross-stratified. Most of the strata are laminated or thin-bedded but in one place a clay bed attains a thickness of about 6 feet.

The cross-stratification shows considerable variation. Most of the cross-strata are laminated. They range from low angle to high angle, small scale to large scale, and the cross-laminations are either straight or concave upward. The straight cross-laminations observed range from a high-angle small-scale set that was 10 inches thick to a low-angle large-scale set that was 8 feet thick. Sets of concave upward cross-laminations observed range in thickness from a few inches up to 12 feet. The dips of the cross-strata observed range from 6 degrees up to a maximum of 32 degrees.

* Terminology for stratification used in this paper is that proposed by McKee and Weir (1953).

Stratification is brought out by differences in grain size, differences in color, concentration of heavy minerals, layers of pebbles or zones of scattered pebbles, thin clayey or silty strata, zones of clay fragments, and strata of clay or silty clay ranging in thickness from a fraction of an inch up to about 6 feet.

Most of the Colma formation is clean sand, but some of it is silty sand and sandy silt. It has a few thin clay beds and gravel beds. Most of the sand is clean, well-sorted, subrounded, and fine to medium grained.

Gravel is found as scattered pebbles or in beds as much as 4 or more feet thick. The gravels commonly have a sandy matrix and in many places are oxidized to reddish-brown or yellowish-orange. Some of the beds appear to be tabular, but most are lenticular and fill channels in the underlying material. The lithology of the pebbles reflects the composition of the source rocks and is different on the two sides of the valley extending from Lake Merced to San Bruno. On the east side where the Colma formation is in contact with rocks of the Franciscan group, the pebbles are angular to subangular and consist mostly of sandstone and chert of the Franciscan with some vein quartz and small well-formed quartz crystals such as are found on San Bruno Mountain. At one locality the gravel contains angular chert fragments as much as 6 inches long. On the west side of the valley where the Colma formation is in contact with the Merced formation, most of the pebbles are soft siltstone and sandstone from the sand and silt in the Merced formation, and well-rounded chert and granite pebbles from the gravel in the Merced formation.

In addition to the sand and gravel, the Colma formation contains silt and clay. Some of the silt and clay is an admixture with sand, forming beds of silty or clayey sand ranging in thickness from a few inches to several feet. Some beds of silt and clay are fairly pure and have only a small admixture of sand. These beds range in thickness from an inch or less up to an observed maximum of 6 feet. Some of these beds appear to be tabular and of uniform thickness whereas others are lenticular and pinch out within a few tens of feet or a few hundred feet. The proportion of silt and clay in the Colma formation seems to be greater in the center of the valley extending from Lake Merced to San Bruno than along the sides, and also greater to the southeast as compared with the northwest.

The Colma formation is more firm and coherent near the surface where it is weathered than at depth where it is fresher. Fresh sand in the Colma is gray or yellowish gray and has little or no cementing material. It is very friable, even loose in places, gullies rather easily, and requires support in excavations, particularly tunnels. Weathered sand in the Colma is yellowish orange or brown, and is cemented with clay and iron oxides so that it is friable to firm or even hard in places, is fairly resistant to erosion, and stands well temporarily in unsupported excavations. Weathering extends downward from the surface for distances of 5 to 50 feet and averages perhaps 15 to 20 feet. In most places weathering has tended to conceal bedding planes so that the sand looks unstratified but in a few places it has accentuated the bedding, particularly where there are ironstone layers. In places in the Colma the previously oxidized sand seems to be undergoing chemical reduction to a depth of about 5 feet. At such places the color is pale yellowish-brown or grayish-yellow, the sand is loose, and greatly resembles dune sand. Pleistocene fossils found near Fleishhacker Zoo in San Francisco (Savage, 1951, p. 282) presumably are from the Colma formation; as the Colma formation is not folded it presumably was deposited after the mid-Pleistocene deformation, hence the formation is probably late Pleistocene in age.

Older Alluvium. Older alluvium forms terraces along the streams in the larger canyons, where it thins rapidly toward the valley walls, but near the heads of the canyons it covers broad areas that extend well up into the highlands. The older alluvium in the highlands may be older than that in the canyons, but subdivision of the alluvium was not feasible. The average thickness of older alluvium is about 25 feet, but in one exposure the alluvium is 45 feet thick. Most of the older alluvium is medium gray in color, but ranges from light gray to dark gray and in a few places is yellowish-orange.

Stratification is not generally visible in this unit. The crude stratification that is visible in places has a low dip, usually 10 degrees or less, but in one place, cross-stratification with dips of 30 degrees was observed. The stratification, where visible, is brought out by differences in resistance to erosion, by color banding, or by lines of pebbles. In most places the lower part of this unit is sandy and has a few beds of gravel; the upper part is silty. The upper part of the unit is the one most often seen and is a compact clayey silty sand or clayey sandy silt, medium gray or dark gray in color, contains scattered pebbles and, in places, fragments of wood and other organic matter. Erosion produces steep-sided spires and columns or knife-edged ridges. In many places the older alluvium is more coherent than the underlying Merced and Colma formations with the result that the streams undercut the older alluvium, which subsequently falls in large blocks, blocking the stream bottom and leaving vertical walls at the sides. The older alluvium is probably of late Pleistocene age.

Recent Alluvium. Recent alluvium forms small deposits in stream bottoms—particularly near their lower ends—and behind artificial barriers such as railroad and highway fills and debris dams. The deposits along the streams are long and narrow but those behind artificial barriers commonly are triangular in outline. In places the alluvium behind artificial barriers contains layers of artificial fill. One of these composite deposits behind an artificial fill on the coast highway is at least 100 feet thick, whereas alluvium along the streams is seldom more than a few feet thick. Inasmuch as the Recent alluvium is derived principally from the Merced and Colma formations, it consists mostly of poorly sorted sand, silt, and some clay. The Recent alluvium is not outlined on the geologic map.

Artificial Fill. Artificial fill is of two general types, here classed as accidental and planned. Accidental fill results from the disposal of unwanted materials and can be exceedingly varied in composition. It may contain natural materials such as soil or rock, or a wide variety of artificial material including automobiles; ac-

cidental fill can be principally cans, garbage, or as in one place, sawdust. The accidental fill, which is not outlined on the geologic map, is in small isolated bodies, perhaps as much as 50 feet thick. Planned fill is built for a definite purpose, such as to raise the altitude or to change the configuration of the ground surface. The material for most planned fill is carefully selected and the material is placed in the fill in such a manner as to give the best end product. In Westlake, planned fill covers broad areas and ranges in thickness from a few feet up to almost 70 feet. The fill in Westlake is made from local materials and hence is principally sand, silt, and clay from the Merced and Colma formations. Most of the fill material was placed in thin layers and compacted by rollers, or tracked or wheeled excavating equipment. Tests made in the completed fill in Westlake show that good compaction was obtained, resulting in a dry density of the fill that was in many cases greater than the dry density of the natural materials in their undisturbed state (table 1).

Structure

Folds.

The Merced formation strikes northwest and dips to the northeast almost everywhere in the cliff exposures between Mussel Rock and Alemany Boulevard. The strike ranges from N. 30° W. to N. 80° E. but most of the strikes are between N. 40° W. and N. 50° W. The dips range from 20 degrees to 75 degrees and most commonly are between 60 and 65 degrees. In the cliff exposures north of Alemany Boulevard the strikes range from due north to N. 60° W., but N. 20° W. is the most common strike. The dips are to the east and northeast and range from 2 or 3 degrees up to 60 degrees, but most commonly are about 20 degrees. The low dips in this northern part of the Merced formation are close to Alemany Boulevard and the steep dips are near the northernmost limits of the formation, close to Lake Merced. This relationship suggests that there is a structural terrace that trends northwest or west-northwest, and passes near the intersection of Alemany Boulevard and Skyline Boulevard.

The marked change in strike and dip near Alemany Boulevard, together with a change in the fossils in this vicinity, has been considered by various workers to indicate that there is a fault or an unconformity in this area. Because of this structural and faunal change, the Merced is considered to have two parts, an upper and lower part; indeed, Londerback (1951, p. 82) suggested that the upper part of the Merced is actually a different formation. The discordance in attitudes can be traced inland to the southeast for a short distance. The cliff exposures in this critical area are very poor, owing in part to landsliding, and the nature of the change cannot be observed directly. However, the marked change in strike and dip seems to take place gradually in a narrow transition zone. Existence of this zone suggests that the upper and lower parts of the Merced formation are not separated by a fault and that the change in fossils is the result of a period of nondeposition or an unconformity.

Faults

Faults traversing the San Francisco peninsula in a northwesterly direction have been mapped by several workers (fig. 1). Some of these faults are known to exist from direct evidence such as offsetting of artificial structures and geologic contacts, but others have been postulated on the basis of geological inferences and may or may not exist in fact.

San Andreas Fault. The San Andreas fault enters the San Francisco peninsula about 0.4 mile north of Mussel Rock and trends southeastward from there. In the San Francisco earthquake of 1906, surface movement along the fault offset roads, pipe-lines, and fences. A fence with an offset of about 5 feet can still be seen along the fault valley 1.3 miles northwest of the south border of figure 1. Accurate surveys made across the San Andreas fault between 1882 and 1946 show that the area west of the fault is moving northwestward relative to the area east of the fault at an average rate of about 2 inches per year. This rate was established by measuring between points 30 to 40 miles apart in four surveys made at approximately 20-year intervals (Whitten, 1955, p. 78). Further evidence of the active nature of the San Andreas fault is the number of epicenters that are located along it (Byerly, 1951, p. 159, fig. 20). The exact position of the San Andreas fault near Mussel Rock is not evident today and it was not evident in 1906 (Lawson, and others, 1908, p. 92). Lawson (1914) shows it in the large gully about 0.4 mile north of Mussel Rock. Inasmuch as the fault zone may be as much as a mile wide, the exact location of the trace of the fault is of little importance; the writer, however, feels that the center of the zone is close to where Lawson mapped it. The center of the fault then is probably 0.8 mile southwest of the intersection of Skyline Boulevard and Westmoor Avenue.

San Bruno Fault. The San Bruno fault (fig. 1) was postulated by Lawson (1895, p. 461-462) to account for the relationship between the Merced formation and the rocks of San Bruno Mountain. The great thickness of the Merced formation (measured as more than 5,000 feet along the beach exposures) seems to dip into and abut against the older rocks of San Bruno Mountain. On the southwest side of San Bruno Mountain, but within the older rocks, a shear zone containing gouge, sheared rocks, serpentine, and other metamorphic rocks suggests a fault. Lawson considered this fault an auxiliary of the main San Bruno fault, which he suggested must be beneath the alluvium west of the mountain. He estimated the throw on the San Bruno fault to be at least 7,000 feet.

The structural terrace in the vicinity of Alemany Boulevard and Skyline Boulevard and other flat dips in the Merced formation to the southeast indicate that the dip of the Merced formation is not consistently northeast as Lawson supposed. Quite possibly, therefore, the Merced formation is folded where it is concealed by younger deposits, and the dip may well be away from San Bruno Mountain rather than toward it. If, as the evidence suggests, there is an unconformity within the Merced formation, then much of the lower part of the Merced formation could have been eroded before the upper part was deposited. Hence, a fault of the magnitude proposed by Lawson is not essential.

The shear zone on the flank of San Bruno Mountain and indirect physiographic evidence indicate that a fault (or faults) of some sort exists on the southwest side of

San Bruno Mountain. Lawson considered the San Bruno fault and its auxiliary fault to be normal faults. Crandall mapped a fault in the same general vicinity as the San Bruno auxiliary fault and termed it a thrust fault with an upthrow of about 1,500 feet on the northeast side (Crandall, 1907, p. 32-33). Crandall thought that the fault was older than the Merced formation (Crandall, 1907, p. 43). Willis states that the San Bruno fault is a thrust fault (Willis, 1938, p. 797). Clearly, the location, displacement, and nature of the San Bruno fault are uncertain. The San Bruno fault and the auxiliary fault east of it are shown on figure 1 as Lawson (1914) mapped them.

Woods Gulch Fault. Ashley (1895, p. 319) mentioned a fault with a throw of 825 feet, downthrown on the south side, at Woods Gulch. Woods Gulch is a short deep gully extending from Skyline Boulevard to the ocean and located about one mile north of Mussel Rock (fig. 1). Ashley also stated that there is evidence of this fault in the ravine which heads against Woods Gulch and flows to the bay (Colma Creek). Crandall also mentions the Woods Gulch fault and shows its location on his geologic map (Crandall, 1907, p. 36, and geologic map). Lawson (1914), in a map published some years after Ashley's and Crandall's papers, did not show the Woods Gulch fault. At the present time, Woods Gulch is largely filled by alluvium and artificial fill so that the head of the gulch is no longer exposed. The alignment of Woods Gulch and the head of Colma Creek has been cited as evidence for the existence of this fault, but as the alignment of the valleys is almost parallel to the strike of the beds the erosion may have taken place along soft beds in the Merced formation, rather than along a fault.

Foothills Thrust Fault. In a paper on the San Andreas fault, Bailey Willis included a map that showed an approximately located fault labelled "Foothills Thrust" (Willis, 1938, p. 794). The approximate position of the fault is shown on figure 1. Willis does not mention this fault in the text but it may be the same fault as the one he called the Stanford fault in an earlier paper. The Stanford fault was exposed in an excavation on the Stanford campus in 1916 and "it has since been traced both north and south skirting the foothills for many miles" (Willis, 1924, p. 163). Willis' paper also has a sketch showing the inferred relationship between the Stanford fault, another thrust fault, and the San Andreas fault (Willis, 1924, p. 163). The Foothills thrust fault was not seen by the writer during the mapping of the San Francisco South quadrangle, but evidence of thrust faulting was observed near the base of the foothills west of San Bruno and about one mile west of the Foothills thrust fault. The Foothills thrust fault as mapped by Willis (1938, p. 794) is shown on figure 1.

EARTHQUAKE DAMAGE

The description of damage in this paper is limited chiefly to such things as landslides, cracks, and arching in natural and artificial materials. Damage to buildings and other structures is treated only in general terms inasmuch as damage of this type is described in detail elsewhere in this Special Report in the reports by Steinbrugge, Bush & Zacher, and by Cloud. Damage of all types was widespread and by no means limited to the area of figure 2.

Landslides

Landslides occurred principally in two places: along the sea cliff between Mussel Rock and Alemany Boulevard, and along the shores of Lake Merced. Several slides above and below the coast highway (fig. 2) trapped two automobiles and closed the road for about 2 weeks. The largest of these slides was a few hundred feet wide and 700 feet (measured along the slope) from top to bottom. Although the slides covered wide areas, they were very shallow and of the types called debris slide and sand run. Most of the slides involved only fine-grained sand, but a few also involved silt and clay. Seasonal rainfall at the time of the earthquake was about 4 inches below normal and the materials were in a dry state; clouds of dust arose as the sliding occurred. The slope of the sea cliff is about 40 degrees and landslides are common in normal years. Evidence of older sliding can be seen on aerial photographs taken in 1943. The earthquake-generated slides resulted from shaking down of dry, loose material on a steep slope that was barely in equilibrium.

Landslides occurred at about a dozen different places along the shore of Lake Merced, and most, if not all, involved artificial fill. The width of the slides ranged from 75 to 300 feet and one series of slides extended along the lake shore for 800 feet. The slides produced scarps that were about 10 feet high. In many of the slides that affected the highway along the lake shore the pavement was rotated so that it dipped away from the scarp rather than toward the scarp as is normal in slump-type landslides. Very little debris from these slides was visible above the level of the lake a few hours after the earthquake. These two conditions support the interpretation that the sliding was in the nature of a flow and that the material spread out on the lake bottom. The material in the scarps was mostly uncompacted artificial fill made up of clean, loose, well-sorted sand which, because it was on the shore of the lake, must have been saturated. This sliding probably was of the type called sand-flow, which results from spontaneous liquefaction of sand. Spontaneous liquefaction is caused by "a collapse of the structure of the sand, associated with a sudden but temporary increase of the pore-water pressure. The liquefaction involves the temporary transformation of the sand into a very concentrated suspension" (Terzaghi and Peck, 1948, p. 100-101). This phenomenon, observed in many parts of the world, can be caused by rapid changes in water level or by vibrations from pile-driving or blasting as well as earthquakes (Terzaghi, 1950, p. 100). Sudden liquefaction of dune sands on Lone Mountain in San Francisco has been attributed to the vibrations caused by streetcars and trucks (Cogen, 1936, p. 468).

In addition to the failures along the roadway at the shore of Lake Merced, the failure of the artificial fill at the north end of the foot-bridge crossing the north arm of the lake also was probably caused by sudden liquefaction of sand. Some of the slides along Lake Merced were of the slump-earthflow type and displayed a backward rotation of the component blocks. These slides may have been caused by removal of support by sudden liquefaction of sand at the foot of the slope.

Cracks and Arching

Although most of the cracks formed during the earthquake were related to movement of artificial fill or landslides, others seemed to be more directly related to earthquake vibrations. The cracks, which were chiefly in pavements and sidewalks, were irregular in detail and, in macadam pavements, broke around the pebbles in the aggregate. None of the cracks seen by the writer showed horizontal movement parallel to the trace of the crack. In Westlake Palisades sidewalks and pavements were locally arched, especially along northeast-trending streets.

Cracks resulting from lurching or settlement of artificial fill occurred principally along the highways but some occurred in residential streets and in stony artificial embankments on the west shore of Lake Merced. Most of the cracks along the highways were on the downhill side, were straight, and either paralleled the center line or trended diagonally toward it. Some, however, were arcuate in plan. In two places in Westlake Palisades cracks were associated with small settlements of the street, sidewalk, and lawns. Small vertical movements occurred along some of these cracks and only horizontal separation in others. Cracks due to lurching or settlement of fills were seen along the coast highway north of Mussel Rock; along Chinese Cemetery Road; along Junipero Serra Boulevard at the intersection with the cemetery road; in Westlake; and southeast of the intersection of Skyline Boulevard and Westmoor Avenue.

Cracks from landsliding occurred near the tops of the scarps of old or new landslides. These cracks were typically arcuate in plan, commonly showed small vertical movements, and in most places were on the downhill side of highways. This type of crack was prominent along the coast highway and along the cemetery road.

Along several of the northeast-trending streets and one northwest-trending street in Westlake Palisades the sidewalks and pavement were arched. The arching may have been caused by compression resulting directly from earthquake waves or by some secondary effect, such as downslope movement of the pavement and sidewalks.

A series of unusual cracks formed southeast of the intersection of Skyline Boulevard and Westmoor Avenue. Most of the individual cracks were less than one-eighth of an inch wide and about 10 feet long, but they were numerous in a wide zone several hundred feet long. The zone and most of the cracks trended northwestward but a few trended northeastward. Older alluvium and sand and clay of the Merced formation, mostly covered with artificial fill, underlie this zone. One northeast-trending crack in sand of the Merced had many tiny rootlets along it, as did tight joints parallel to the crack. The rootlets are evidence that the crack was merely a joint that had been opened up by the earthquake vibrations. Northwest-trending cracks, which were seen only in artificial fill, may also have resulted from opening up of joints or bedding planes in natural materials underlying the fill.

Another unusual type of crack was observed in the shoulder of the coast highway just south of Woods Gulch. Here the ground was irregularly fragmented as though an explosion had been set off beneath it (photo 1).

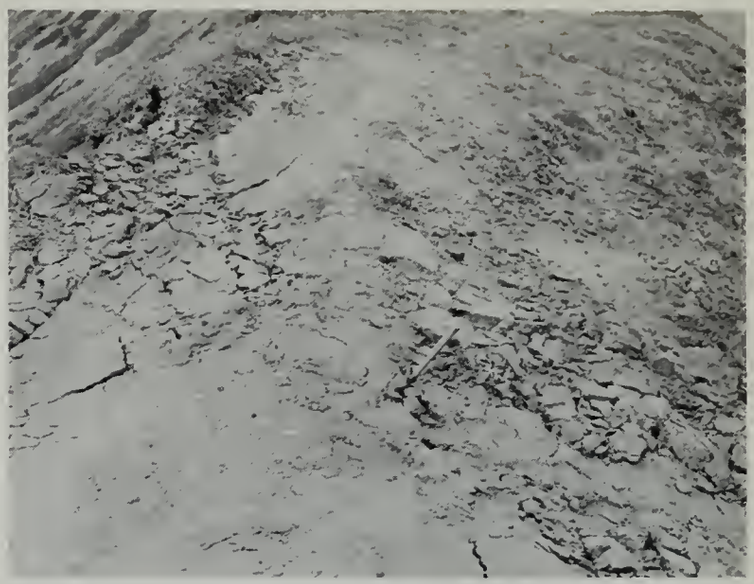

Photo 1. Fragmentation of ground along coast highway just south of Woods Gulch, San Mateo County.

Relationship of Damage to Foundation Material

The Westlake area received the greatest damage during the earthquake. Although the severity of damage was just as great in other parts of the San Francisco peninsula, the density of damage was greatest in the Westlake area, particularly in Westlake Palisades, where about half the houses were damaged.

Within Westlake Palisades the intensity and frequency of damage varied considerably from place to place. The developer of the tract had an engineering firm make a detailed survey of the damage in Westlake Palisades. Each house was rated on an arbitrary scale ranging from 0 (no damage) to 10 (maximum damage). The scale, which is reproduced in figure 3, contains several grades whose descriptions are identical but the engineers who made the survey said that the apparently identical grades were differentiated on the basis of differences in sizes of cracks. The ratings for 568 houses were plotted on a map showing areas of cut and areas of artificial fill. The average value for the houses in the cut areas was 4; for the houses on artificial fill, 2; and for houses that were on the line between cut and fill, 4 (written communication, Theodore V. Tronoff, Civil Engineer). Here, then, is a case where structures on artificial fill were generally damaged less than structures on natural materials. The average dry density of the sand which makes up the bulk of the artificial fill is greater than the dry density of the sediments in the Merced formation (table 1). This greater density may be part of the reason for the lesser damage on artificial fill, although even greater density contrasts within the Merced formation did not seem to have a consistent effect on the amount of damage.

In the few instances where it was known that certain houses were founded on clay of the Merced formation and adjacent ones were on sand of the Merced formation, the difference in damage was not consistent. Perhaps the bands of clay and sand were too narrow for the differences in their physical properties to be reflected in the damage ratings, whereas the broad areas of artificial fill permitted its physical properties to affect the damage.

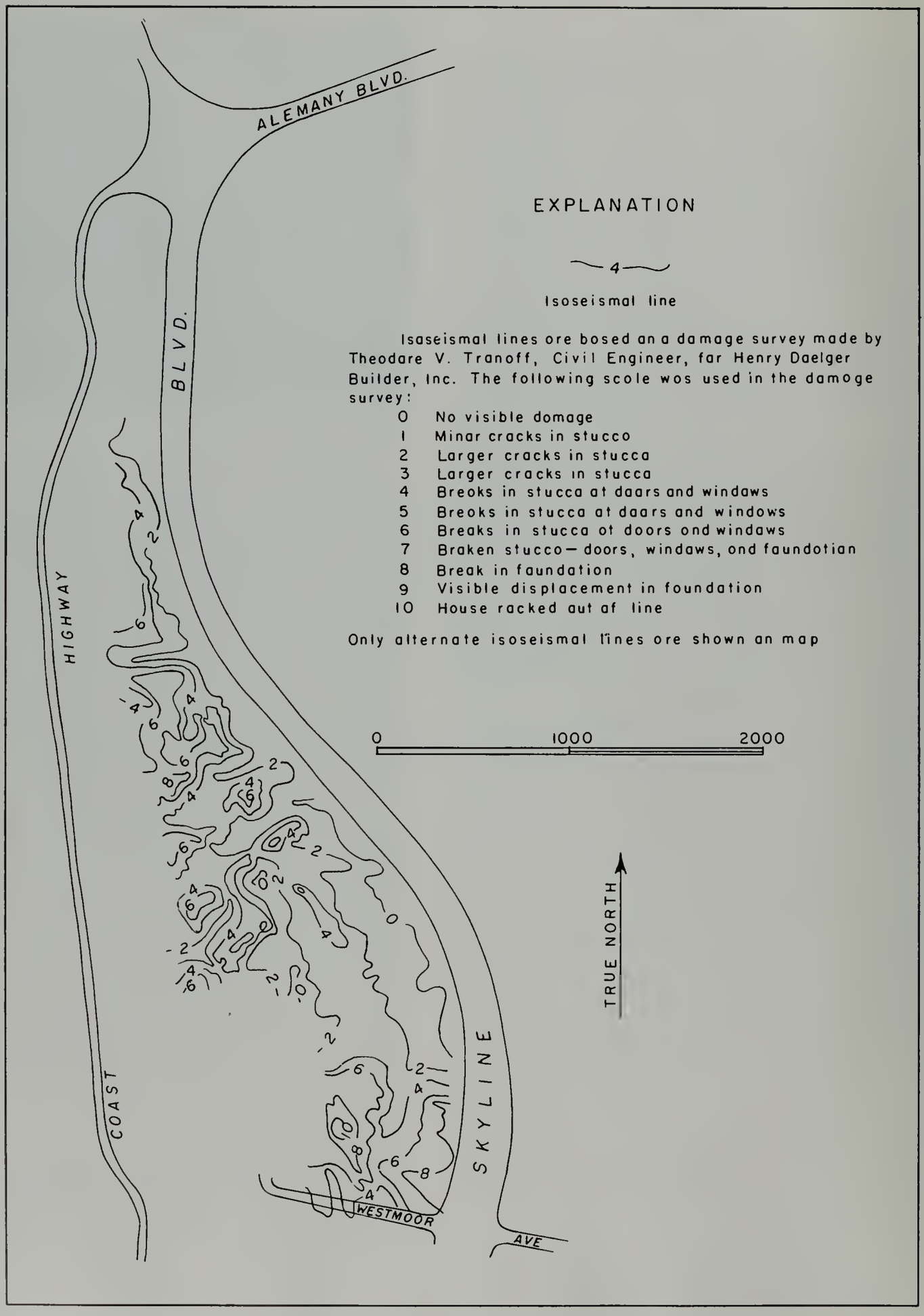
ALEMANY BLVD.
BLVD.
HIGHWAY
COAST
SKYLINE
WESTMOOR
AVE
EXPLANATION
4
Isoseismal line
Isaseismal lines ore bosed an a damage survey made by Theodare V. Tranoff, Civil Engineer, far Henry Daelger Builder, Inc. The following scole wos used in the damoge survey:
0 No visible domage
1 Minar cracks in stucco
2 Larger cracks in stucca
3 Larger cracks in stucca
4 Breoks in stucca at daars and windaws
5 Breoks in stucca at daars and windows
6 Breaks in stucca ot doors ond windaws
7 Braken stucco — doors, windaws, ond faundotian
8 Break in faundation
9 Visible displacement in foundation
10 House racked aut af line
Only alternate isoseismal lines ore shown an map
0
1000
2000
TRUE NORTH

FIGURE 3. Isoseismal map of Westlake Palisades, Daly City.

To investigate further the relationship between damage and rock type in natural ground, the writer constructed an isoseismal map of Westlake Palisades (fig. 3) using the data supplied by Mr. Tronoff. The isoseismal lines show a tendency for elongation parallel to the strike of the beds in the Merced formation, suggesting to the writer that rock type did have some influence on damage; however the isoseismals are also oriented parallel to the streets, which run northeast and northwest. Such parallelism of the streets and isoseismals suggests to the writer that the earthquake-resistance of the houses was not the same in all directions and that orientation of the houses with respect to the streets influenced the pattern of damage. Parallelism of the streets and isoseismals may also result in part from subjective errors in the damage survey and the spacing of the data on which the isoseismal map was made.*

The greater damage in Westlake Palisades as compared to the rest of Westlake is difficult to explain. The foundation materials are similar, the houses are similar in design and made of the same materials by the same contractor. A few of the houses in Westlake Palisades were so new that the stucco had not yet hardened thoroughly. This fact may explain some of the greater damage to stucco in Westlake Palisades, but does not explain displacement of foundations nor houses racked out of line. The later two effects occurred only in Westlake Palisades.

The greater damage in Westlake Palisades may be related in some way to the sea cliff that bounds the area on the west. Earthquake waves, emerging almost vertically in this epicentral area, may have been reflected eastward by the inclined cliff face, resulting in a concentration of earthquake effects in Westlake Palisades; effects due to motion of the free face of the cliff may have increased the damage close to the cliff. Steinbrugge, Bush, & Zacher have suggested elsewhere in this report that the localization of damage may be related to large-scale lurch effects. A combination of these mechanisms and the fact that some of the stucco had not yet hardened thoroughly may be the cause of the greater damage in Westlake Palisades.

No data are available on the position of the water table, but presumably it was at a greater depth below the surface in Westlake Palisades inasmuch as the surface elevations are greater there and the surface of the water table tends to be flatter than the ground surface.

Relationship of Damage to Faults

Shortly after the earthquake the writer examined the San Andreas fault, the vicinity of the San Bruno fault, and some of the area between the two faults. No surface evidence of new movement was found. The instrumental epicenter of an earthquake can be located within about 3 kilometers (nearly 2 miles) under favorable conditions (Benioff and Gutenberg, 1955, p. 134). In this earthquake, the location of the instrumental epicenter reported by the University of California Seismograph Station (shown on fig. 1) may be in error by about 3 miles (Don Tocher, oral communication), so that the focus may have been on some fault other than the San Andreas (fig. 1). The landslides around Lake Merced are considered by some geologists as evidence for faulting along the San Bruno fault but, as has been shown above, the type of sliding that was prevalent at Lake Merced can be activated by very feeble shocks. The purportedly linear distribution of the damage in Westlake Palisades, together with the series of cracks southwest of Westlake Palisades and on Junipero Serra Boulevard, have been cited by some geologists and laymen as evidence that the earthquake originated on a fault passing through Westlake. Study of the detailed damage data from Westlake Palisades and of the isoseismal map constructed from those data fails to reveal any sharp linear pattern to the damage distribution. The cracks extending southeastward from Westlake Palisades can be explained by means other than faulting. With the lack of conclusive evidence to the contrary, it is reasonable to conclude that the earthquake originated along the one fault that is known to be active, the San Andreas.

In this area of active faults and great construction activity, it is well to redirect attention to an important paper on faults and earthquakes (Louderback, 1942). Louderback showed that the intensity of an earthquake is not necessarily highest at the surface trace of the earthquake-generating fault and that active faults do not necessarily produce destructive shocks. He suggested that destructive earthquakes probably are generated only at some depth in the earth, perhaps on the order of 5 miles or more. If the structure is not astride an active fault, it matters little whether it is alongside the trace of the fault or a mile away, because the energy reaching the surface will be almost the same at the two points. Intensity depends, among other things, on the attitude of the fault and the distribution of near-surface geologic conditions, including rock types and structures, so that proximity to a fault should not be given undue weight when deciding where to build.

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* *Editor's note:* The California State Division of Highways, Lew Wulff, Senior Highway Engineer, Materials and Surveys, has contributed the following note to the Division of Mines on soil conditions in the Westlake Palisades area:

"The soils throughout the area are quite uniform in physical characteristics and are classified as sandy loams on the United States Bureau of Public Roads chart.

"Specifically, the soil falls into the fine sand classification with all particles passing the No. 50 U. S. standard sieve. An average of 45 percent by weight passes the No. 200 U. S. standard sieve, which fraction is composed mostly of sand and silt.

"The soil is readily compacted when pneumatic-tired compacting equipment is used in construction of fills. Past experience in construction of fills in this area indicates that a cubic yard of material in cut makes a cubic yard of material in fill or, in other words, the density of the material in fill is comparable to the density of the material in cut. Inasmuch as Mr. Tronoff's damage survey indicates a greater severity of damage was suffered by residences founded on undisturbed soil, some sort of explanation would be desirable. It is generally recognized that re-molded specimens of soil do not exhibit the same characteristics when subjected to the various physical tests, such as unconfined compression, shear and similar tests even though they may be fabricated at the same density as in-place material. Engineered fills may be considered as re-molded material and therefore may exhibit marked differences of behavior from that of in-place material in transferring or absorbing a seismic shock.

"In reference to the damage done to the State highways, it may be said that slide removal and roadbed repairs amounted to $40,000 in the Thornton Bluffs section and $5,000 to $10,000 in the Lake Merced area. Inasmuch as the Thornton Bluffs are standing on slopes which, in the opinion of this writer are very close to the maximum angle of recline for this type of soil, it is not surprising that slides occurred during the earthquake. Minor slides have been occurring along this section of highway for years, to the extent that its position is rapidly becoming untenable."

SEISMIC HISTORY OF THE SAN FRANCISCO REGION

By Don Tocher, Seismologist
University of California, Berkeley
Seismograph Station

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ABSTRACT

The historical record of eathquakes in the Coast Ranges of California adjacent to San Francisco and Monterey Bays reveals that moderately strong shocks (as strong as or stronger than the earthquake of March 22, 1957) were far more frequent in the years immediately preceding the major earthquakes of 1868 and 1906 than in the years immediately afterward. The instrumental record is not nearly as long as the historical record; but the latter gains some support from the former in that the five shocks since 1942 which were strongest from the non-instrumental standpoint were also strongest on the instrumental magnitude scale.

During the same period (1942-57) almost all of that portion of the Hayward fault from San Leandro to Warm Springs which broke in the earthquake of 1868 has been remarkably quiet seismically in comparison with adjacent portions to the north and south. That portion of the San Andreas fault from San Juan Bautista to Humboldt County which broke in 1906 has been equally quiet with the exception of the southern 20 miles and two isolated sections, one near Palo Alto, the other between San Bruno and Bolinas. The source of the earthquake of March 22, 1957 was at the southern end of the San Bruno-Bolinas section.

INTRODUCTION

The earliest records of earthquakes in California are necessarily non-instrumental. Seismographs were not introduced to the region until 1887, when the first stations anywhere in the Western Hemisphere were established on the Berkeley and Mount Hamilton campuses of the University of California. While the original installations included the best seismographs then available, sensitivity was very low by present-day standards; earthquakes were not recorded at all unless either very strong or very close to one of the stations. Relatively accurate instrumental locations did not become available until comparatively recent years, as more sensitive seismographs and additional stations were installed in central California and surrounding regions. An interesting historical account of the development of seismometry in California is given by George D. Louderback in his *History of the University of California Seismographic Stations and Related Activities* (1942).

The most complete collection of non-instrumental data through 1927 is the catalogue of Townley and Allen (1939). For later years, non-instrumental reports have been published annually under the title *United States Earthquakes* by the U. S. Coast and Geodetic Survey, Washington, D. C.

The following list has been abstracted mainly from these sources, and includes shocks that were, or probably were, of destructive intensity. Especially for shocks in the earlier years, the imperfect historical record is often not clear-cut, either as to the strength or the extent of the shaken area. The arbitrary lower limit of intensity for shocks in this list is VII, as judged by the compilers of the lists cited above,* or in other sources.

RECORD OF MAJOR SHOCKS, 1800-1957

1800 October 11. Strong shocks at San Juan Bautista, continuing at least through October 31. Every building damaged; cracks appeared in the ground of the rancheria, and a deep fissure near the Pajaro River.

1808 June 21. Eighteen shocks at the Presidio of San Francisco up to July 17. Adobe walls were seriously damaged (VIII). Date of main shock not known.

1822. The church at the Santa Clara Mission was badly injured. The Mission San Jose may also have been damaged by this shock.

1836 June 10, 7:30 a.m. One of the five largest earthquakes centered in the San Francisco Bay region in historic times. Ground breakage along the line of the Hayward fault at the base of the hills east of the bay, extending from Mission San Jose to San Pablo. As strong or stronger than the shock of October 21, 1868, which had its center along the same fault. At least one foreshock; numerous aftershocks for at least a month.

1838 June. Just after noon. Another of the five largest shocks in the area. Surface breakage along the San Andreas fault zone, probably extending at least from San Francisco to a point near Santa Clara. Serious damage to walls at the Presidio of San Francisco and at the Missions San Jose, Santa Clara, and San Francisco. Comparable with the earthquake of April 18, 1906.

* This means VII, Rossi-Forel for shocks through 1930, and VII, Modified Mercalli for 1931 and later. As VII, Rossi-Forel corresponds to the higher grades of VI, Modified Mercalli, the difference is not great.

PHOTO 1. Canyon offset by repeated movements of the Hayward fault. The ridge in front of the deflected canyon segment was produced by offsetting the end of the right spur. Looking east from the Hayward-Niles highway. *Photo by Richard J. Russell (Division of Mines Bulletin 154, fig. 19, p. 158).*

1841 July 3, 2:07 p.m. Intensity VII at Monterey. Also felt at sea.

1851 May 15, 8:10 a.m. Severe shocks (VII) at San Francisco. Also felt on ships in the harbor.

1851 November 26. Eleven shocks felt along the coast from Santa Cruz to Mendocino. This may be an incorrect reference to strong shocks in southern California on October 26, 1852, or November 27, 1852. None of the 11 are known to have been destructive.

1852 November 22, 11 p.m. Intensity VIII on the San Francisco peninsula. Severe 8 miles to southwest of San Francisco, where considerable fissuring of the ground allowed the waters of Lake Merced to drain into the ocean.

1856 February 15, 5:25 a.m. Intensity VIII at San Francisco, where there was considerable building damage. Felt from Santa Rosa south to Monterey, and as far east as Stockton. Water in San Francisco Bay disturbed.

1858 November 26, 12:35 a.m. At San Jose (VIII) nearly every brick, adobe, or masonry building was cracked or injured in some way. There was some damage to buildings in San Francisco (VII), especially on made land.

1859 October 5. Intensity in San Francisco has been estimated as VII, although details are lacking.

1861 July 3, 4:11 p.m. Intensity IX (?) near the present site of Livermore. Adobe houses damaged, men in the fields thrown down.

1864 March 5, 8:49 a.m. Widely felt, but apparently strongest at San Francisco (VII+). Intensity VII at San Jose and Santa Clara, VI at Stockton. At San Francisco, plate glass windows were shattered and plaster cracked.

1865 March 8, 6 p.m. Intensity VIII in east-central Sonoma County. Severe in Santa Rosa and upper Bennett Valley, a few miles from Santa Rosa. Plaster cracked, clocks stopped, and chimneys thrown down.

1865 October 8, 12:44 p.m. One of the five largest earthquakes in the region in historic times, and first of the two large shocks of the 1860s. Apparently centered on the San Andreas fault in the Santa Cruz Mountains, where cracks in the ground, landslides, and dust clouds were observed. Intensity at least IX. In San Francisco,

damage was most severe on made ground; the Old Merchants' Exchange Building at Battery and Washington Streets was ruined, and a fissure appeared in the ground on Howard Street from Seventh to Ninth.

1866 March 26, 12:30 p.m. Felt in San Francisco, Stockton, Monterey, Sacramento, and San Jose. Minor damage may have occurred in San Francisco, though existing reports do not agree sufficiently well to estimate the maximum intensity.

1868 October 21, 7:53 a.m. One of California's great shocks, and second of the two large Bay Area shocks of the 1860s. Surface breakage was observed on the Hayward fault from Warm Springs to San Leandro, a distance of about 20 miles. The maximum horizontal offset was about 3 feet. Intensity X at Hayward, where every building was damaged, and many demolished. Intensity IX at San Francisco, where, as in earlier large shocks,

Photo 2. Buildings in Heywood (now Hayward) wrecked by the earthquake of October 21, 1868. *From a photograph preserved by Mr. H. Bendel.*

damage was chiefly confined to buildings on filled ground along the bayshore. About 30 persons lost their lives in this shock. This earthquake was felt at places 175 miles from the source.

1882 March 6, 2 p.m. Newspaper reports suggest an epicenter near Hollister, with an intensity there of VII. Felt to the southeast at least as far as San Luis Obispo and Visalia.

1883 March 30, 7:45 a.m. Intensity VII at Hollister. Plaster knocked loose and windows broken. Also strong at Watsonville and Santa Cruz. Felt from Martinez to San Luis Obispo.

1884 March 25, 4:40 p.m. Severe, possibly VII, at San Francisco. Felt from Santa Cruz to Petaluma, and at Grass Valley.

1885 March 30, 11:56 p.m. Intensity VIII at Mulberry, on the San Andreas fault southeast of Hollister, where chimneys were thrown down. Plaster fell at Hollister (VII), and the soft river banks were fissured extensively at the junction of the Pajaro and San Benito Rivers.

1885 July 31, 4:10 p.m. Intensity VII at Cloverdale, Sonoma County. Details lacking.

1888 February 29, 2:50 p.m. Intensity VII or perhaps VIII at Petaluma, where walls were cracked. Strong at a number of points north and west of the bay.

1888 November 18, 2:28 p.m. Five chimneys knocked down along 23d Avenue in Oakland. This shock was not felt over a very wide area.

1889 May 19, 3:10 a.m. Strongest at Antioch and Collinsville (VIII), where chimneys were damaged, plaster cracked, and crockery and glassware broken. Slight damage at Lodi, Napa, Rio Vista, and San Francisco. Felt over a wide area in central California.

1889 July 31, 4:47 a.m. Intensity VII in the San Francisco Bay region. One chimney fell in San Leandro; the brick pier of the 8-inch telescope at Chabot Observatory in Oakland was cracked. Felt from Gilroy to Santa Rosa.

1890 April 24, 3:36 a.m. Intensity VIII to IX in the Monterey Bay region. Many chimneys down at Watsonville, with somewhat less damage at Gilroy and Hollister. Ground fissures in the San Andreas fault zone near Chittenden. The railroad bridge over the Pajaro River was displaced, and nearby track moved. Felt from Salinas to Santa Rosa.

1891 January 2, 12:00 m. Ceilings cracked and plaster down at Mount Hamilton (VII). Strong, but no significant damage at San Jose, Gilroy, and Lathrop (San Joaquin County).

1891 October 11, 10:28 p.m. Intensity VIII to IX at Sonoma and Napa. More or less damage to every house in the Sonoma Valley, where chimneys fell and people were thrown from their beds.

1892 April 19, 2:50 a.m. Intensity IX to X in Solano and Yolo Counties. In Vacaville, nearly every brick building was wrecked, and many frame buildings damaged. The shock was nearly as severe at Dixon and Winters. This was probably the largest shock in the San Francisco Bay region between 1868 and 1906. Felt from Fresno to Healdsburg, and east to western Nevada.

1892 April 21, 9:43 a.m. A very strong aftershock of the preceding earthquake. Intensity was fully IX at Winters, where many buildings which withstood the earthquake of April 19 were totally wrecked. At Vacaville, 12 miles south of Winters, damage was considerably less than on April 19. Felt from Fresno to Red Bluff, and east to Reno.

1892 November 13, 4:45 a.m. Intensity VII+ at Monterey, where chimneys were cracked. Minor damage at Salinas and Hollister. Felt as far north as Petaluma.

1893 August 9, 1:15 a.m. Intensity VII to VIII at Santa Rosa, where chimneys fell, windows were broken, and plaster was damaged.

1897 June 20, 12:14 p.m. Felt from Napa and Sacramento south to Templeton, and east to Modesto, Merced, Fresno, and Visalia. Source probably on the San Andreas fault in San Benito County. Intensity VIII to IX at Hollister, where nearly every brick building was damaged, and at Salinas, where walls and chimneys were thrown down.

1898 March 30, 11:43 p.m. Considerable damage at Mare Island Navy Yard (VIII), where only the late hour of occurrence averted many fatalities. Chimneys twisted and considerable minor damage in San Francisco (VII). Felt over much of central California, and at Carson City, Nevada.

1899 April 30, 2:41 p.m. Epicenter probably on the San Andreas fault northeast of Watsonville. Intensity VII to VIII at Watsonville and toward Corralitos;

PHOTO 3. Road across head of Tomales Bay offset 21 feet by movement on the San Andreas fault on April 18, 1906. *Photo by G. K. Gilbert.*

chimneys and cemetery monuments damaged in Green Valley.

1899 July 6, 12:10 p.m. Two separate shocks within one minute of each other. One, apparently centered a few miles south of the earthquake of April 30, 1899, knocked down chimneys in Watsonville and broke lamps and windows at Salinas. The other was a very local shock, but did more or less damage to nearly every brick building in Pleasanton, 50 miles north of Watsonville.

1899 October 12, 9 p.m. Plaster knocked from walls and some chimneys down at Santa Rosa (VII to VIII). Some damage in Petaluma.

1902 May 19, 10:31 a.m. Intensity VIII at Elmira, Solano County, where nearly all chimneys were thrown down; VII to VIII at Vacaville, VII at Fairfield and Suisun.

PHOTO 4. O'Farrell Street, San Francisco, after the earthquake and fire of April 1906. Most of the buildings visible in the photograph sustained relatively minor damage from the earthquake, but later were destroyed by the fire.

1903 June 11, 5:12 a.m. Epicenter probably on the Hayward or Sunol (Calaveras) faults north of San Jose. Intensity VIII. Chimneys down in San Jose, Hayward, Livermore, and near Niles.

1903 July 24, 12:26 p.m. Several brick walls were cracked and much plaster fell at Willows (VII).

1903 August 2, 10:49 p.m. Intensity VIII at San Jose and Mount Hamilton. In San Jose, there was much damage to brick and stone buildings and to chimneys. Chimneys fell and plaster was cracked at Mount Hamilton. Felt over an area of about 50,000 square miles.

1906 April 18, 5:12 a.m. One of the greatest shocks in California, caused by movement on the San Andreas fault between San Juan Bautista and southern Humboldt County. Maximum horizontal ground offset at the fault was 21 feet, near the head of Tomales Bay. The ground southwest of the fault moved toward the northwest relative to the northeast side. Vertical movement was small (not more than 3 feet), and was generally confined to the region northwest of the Golden Gate.

At least 700 fatalities were caused by the great shock and the ensuing fires; about 400 of these were in the City of San Francisco. Various estimates of total damage in San Francisco range from $350 million to $1 billion. Estimates of the loss due to earthquake exclusive of fire ranged from 5 to 20 percent of the total, with 10 percent being the figure chosen more than any other.

In general, well-constructed structures received only minor damage, which shows that it is possible to build structures that will safely withstand the shaking from an earthquake of this magnitude. This does not apply, of course, to structures built directly on the fault line. With the possible exception of a low, broad earthen dam, no structure built by man can stand up under differential displacement of its opposite parts of 20 or even 10 feet. It is fortunate that the trace of the San Andreas fault traverses regions which, in 1906, were quite sparsely inhabited, so that there were only a handful of structures rent asunder by the fault break itself. Even now, there are only two relatively short sections of the San Andreas fault which have more than a very few buildings in the immediate vicinity of the trace of the 1906 break, one between Pacifica and San Bruno, and the other in the vicinity of Woodside. (The situation on the east side of the Bay is not such a happy one. Portions of the Hayward fault which broke in 1836 and 1868 traverse what are today high-density residential areas from Hayward to San Pablo.)

1910 March 10, 10:52 p.m. Intensity VII in the Monterey Bay region, strongest at Aptos and Watsonville, but nearly as strong in much of the Pajaro Valley. Nearly everywhere in the epicentral region the motion was a slow rocking of alarming energy. Although the intensity nowhere exceeded VII, the shock was perceptible over an area of more than 60,000 square miles, suggesting either that the focus was rather deeper than usual for a California earthquake, or that the focus was well offshore in Monterey Bay.

1911 March 11, 1:30 p.m. Plaster cracked, some damage to chimneys, and things knocked from walls at Hollister (VII).

1911 July 1, 2:00 p.m. Intensity VIII to IX at Coyote in the Santa Clara Valley. In the region around

San Jose, Gilroy, and Morgan Hill, the intensity was VII to VIII; many chimneys were destroyed and some brick walls cracked. The 36-inch refracting telescope at Mount Hamilton shifted three-quarters of an inch on its base, and a three-story brick dormitory building was damaged so badly that it had to be condemned. According to Gutenberg and Richter (1954), the instrumental magnitude of this shock (6.6) was higher than any in central California since 1906. The epicenter was most likely on the Hayward fault in the rugged hills east of Coyote. The shock was felt over 60,000 square miles.

1914 November 8, 6:31 p.m. Intensity VIII at Laurel in the Santa Cruz Mountains. Felt from St. Helena south to Soledad. Epicenter probably on the San Andreas fault near Laurel.

1916 August 6, 11:38 a.m. Intensity VIII at Paicines, VII at Hollister. Region of perceptibility about 30,000 square miles.

1926 October 22, 4:35 a.m. Center on the continental shelf off Monterey Bay. Intensity VIII at Santa Cruz, where many chimneys were thrown down; VII at Capitola, Monterey, Salinas and Soquel. Felt from Healdsburg to Lompoc, and east to the Sierra, an area of nearly 100,000 square miles. Another shock one hour later was similar in almost every respect to the first.

Photo 5. Damage to adobe walls of old winery near Hollister; earthquake of June 24, 1939. *Photo by U. S. Coast and Geodetic Survey.*

1933 May 16, 3:47 a.m.* Intensity VIII near Overacker Station, between Niles and Irvington, where all chimneys were down and other damage was done to buildings, and in Niles Canyon, where rockfalls blocked the road. Intensity VI to VII at Hayward, Martinez, Mission San Jose, and Walnut Creek.

1937 March 8, 2:31 a.m. Damage to chimneys, plaster, retaining walls, and sewers in north Berkeley, Albany, and El Cerrito (VII). Felt over an area of 5,000 square miles.

1939 June 24, 5:02 a.m. Epicenter on the San Andreas fault 7 miles south of Hollister. Damage to chimneys of farmhouses and to the walls of a winery building in a small area south of Hollister (VII). Some cracks in the ground.

1949 March 9, 4:28 a.m. Felt over an area of 20,000 square miles from Santa Rosa south to Santa Margarita. At Hollister (VII) damage consisted of fallen chimneys, cracked walls, sprung elevator shafts and door frames, and broken windows. Intensity was VI over a rather wide area from Pinole to Soledad.

1954 April 25, 12:33 p.m. Intensity VIII in a small region along the Chittenden Road on the south bank of the Pajaro River. Several houses severely damaged, ground cracked, and loose earth slid onto the road. Epicenter doubtless on the San Andreas fault, which crosses the Pajaro River at this point. Felt over 12,000 square miles from Santa Rosa to San Ardo, and east to Fresno.

1955 September 4, 6:01 p.m. Damage at San Jose (VII) consisted mainly of damaged chimneys (75 in the Willow Glen district, east of San Jose) and cracked walls. Some underground pipe damage. Felt from Santa Rosa to San Ardo and east to Madera.

1955 October 23, 8:10 p.m. Epicenter between Walnut Creek and Concord. Maximum intensity VII; moderate property damage (estimated at $1,000,000) over a considerable area. Damage was mostly confined to broken windows, cracked walls and plaster, and loss from broken merchandise. A few chimneys were knocked down, including two in Berkeley. Felt from the Carmel Valley to Zamora, and east to Copperopolis.

1957 March 22, 11:44 a.m. Epicenter on the San Andreas fault near Mussel Rock. Principal building damage was to frame houses in the Westlake Palisades tract west of Daly City. Damage was principally exterior plaster cracks, but several dwellings sustained more serious structural damage, and a number of chimneys were cracked.

INTERPRETING THE RECORD

Whether or not an earthquake has been included in the foregoing list has been decided solely on the basis of the reported intensity, or the non-instrumental aspects of the shock. A serious drawback to attempting to use such a list for statistical purposes lies in its non-instrumental character. Some shocks which release relatively minor amounts of energy are included by the geographical accident of being centered in a populous

* Commencing with this shock, intensities listed are based on the Modified Mercalli scale. For a description of this scale, and a comparison with the older Rossi-Forel scale, see Wood and Neumann (1931).

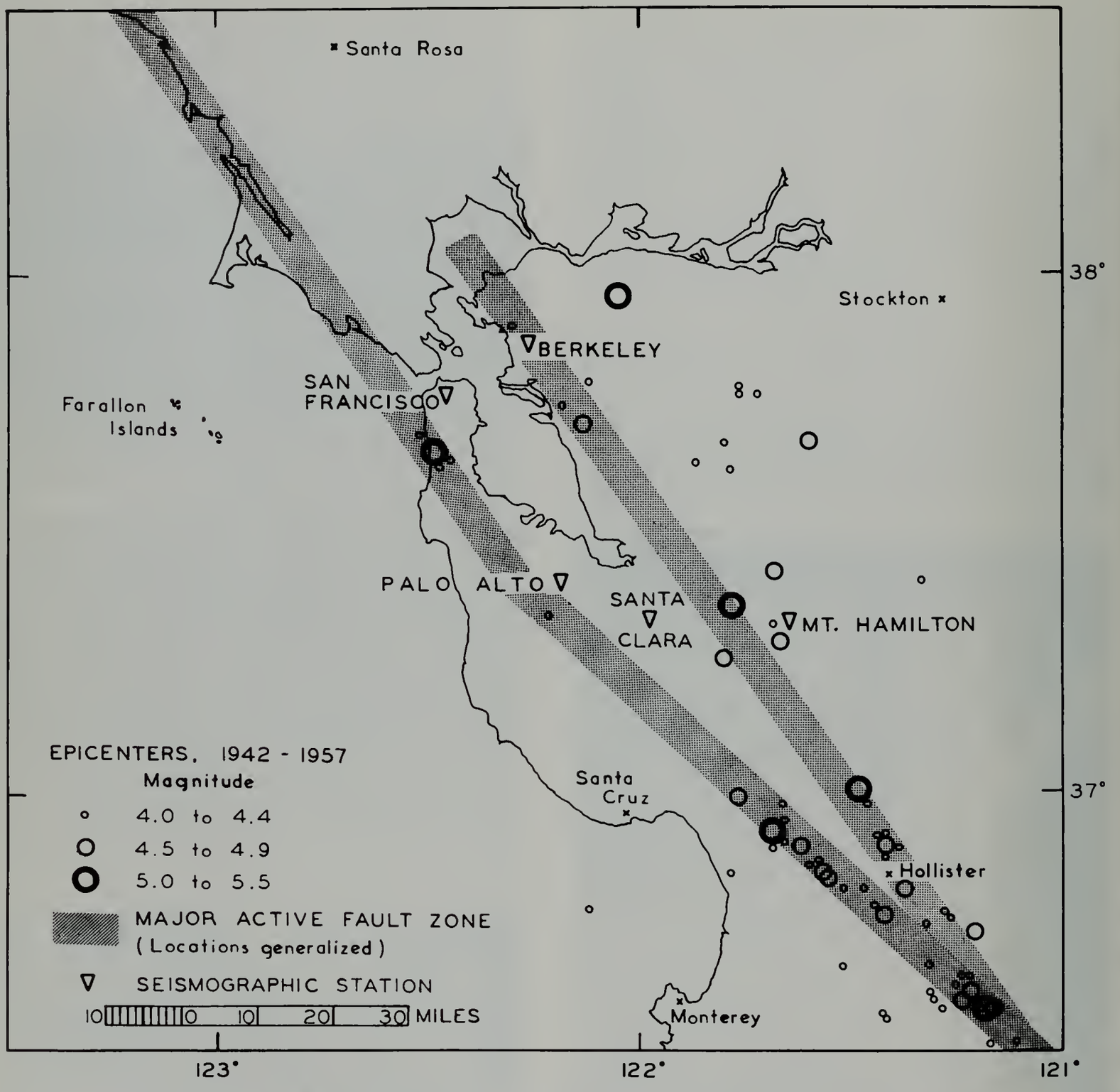

FIGURE 1. Map showing epicenters of larger earthquakes in central California, 1942-1957.

*Table 1. Epicenters for shocks, magnitude 4.0 or greater, 1942-57, as located by seismographic triangulation.**

Origin time (G.C.T.) Date	h.m.s.	N. Lat. ° ′	W. Long. ° ′	Magnitude	Quality
1942					
Jan. 14	09 44 40	36 39	121 13	4.2	b
Apr. 8	14 20 14	36 36	121 18	4.0	a
Apr. 11	08 40 59	36 45	121 19	4.0	b
June 5	12 33 25	36 59	121 40	4.2	b
Dec. 29	18 18 14	37 43	122 07	4.3	a
1943					
Mar. 29	11 45 55	37 38	121 52	4.2	a
Apr. 15	15 23 04	37 41	121 46	4.0	a
Apr. 15	15 31 02	37 41	121 46	4.1	a
Apr. 21	23 39 44	37 41	121 43	4.2	a
Apr. 26	11 54 00	37 37	121 47	4.1	a
Oct. 26	04 50 33	37 26	121 41	4.9	b
1944					
June 7	12 35 38	36 35	121 17	4.0	b
1945					
Jan. 7	22 25 33	36 44	121 12	4.7	b
May 17	15 06 47	36 49	121 22	4.6	b
Aug. 27	09 13 04	37 16	121 48	4.5	c
Nov. 3	15 50 22	36 38	121 15	4.2	c
Nov. 8	20 09 17	37 10	121 31	4.2	c
1946					
Feb. 10	11 01 19	36.5	121.1	4.2	d
May 2	01 26 12	37 41	121 36	4.6	a
May 29	17 51 03	36 46	121 25	4.5	c
Aug. 5	04 08 45	36 51	121 47	4.1	c
1947					
June 22	23 29 33	37 00	121 46	4.7	a
July 7	04 04 30	36 46	121 25	4.3	a
Aug. 10	21 58 24	36 53	121 25	4.4	a
Nov. 15	22 29 37	36 47	122 07	4.1	b
1948					
Mar. 28	22 36 21	36 51	121 34	4.0	b
Mar. 28	22 38 03	36 51	121 34	4.6	a
Mar. 28	22 45	36 51	121 34	4.5	c
Apr. 27	16 41 08	36 46	121 16	4.0	a
Apr. 27	20 22 25	36 46	121 16	4.4	a
June 11	08 28 11	36.6	121.2	4.0	d
1949					
Jan. 1	01 17 54	36 54	121 37	4.5	b
Mar. 9	12 28 39	37 01	121 29	5.2	b
Mar. 14	06 10 15	37 01	121 29	4.4	b
June 10	03 06 40	37 18	121 40	4.6	b
June 22	18 08 46	37 20	121 41	4.1	b
Oct. 22	21 45 20	36 35	121 10	4.7	c
1950					
Sept. 30	21 26 33	36 54	121 23	4.1	b
Nov. 23	13 58 24	36 49	121 31	4.1	c
1951					
July 29	10 53 45	36 35	121 11	5.0	b
Aug. 6	09 05 02	36 37	121 13	4.9	b
Oct. 30	19 55 14	36 54	121 25	4.0	a
Oct. 30	19 59 18	36 54	121 25	4.2	b
Oct. 31	20 58 19	36 54	121 25	4.8	a
1952					
Oct. 13	00 34 09	37 45	122 11	4.2	b
Oct. 22	00 45 52	37.9	122.3	4.0	d
1953					
Mar. 16	08 52 06	36 57	121 40	4.0	b
May 25	00 23 30	36 49	121 28	4.0	b
Dec. 17	05 13 12	36 55	121 40	4.2	a
1954					
Mar. 27	15 43 31	36 31	121 10	4.4	c
Apr. 10	22 16 53	37 11	121 48	4.1	a
Apr. 22	18 50 13	36 54	121 41	4.3	b
Apr. 25	20 33 28	36 56	121 41	5.3	b
June 22	11 49 29	36 34	121 25	4.4	a
June 22	12 50 04	36 34	121 25	4.3	b
July 29	08 51 36	37 25	121 20	4.2	b
Dec. 17	07 08 58	37 43	122 08	4.5	b
1955					
Sept. 5	02 01 18	37 22	121 47	5.5	b
Oct. 24	04 10 44	37 58	122 03	5.4	a
1956					
Feb. 18	23 58 30	36 40	121 19	4.2	b
Oct. 19	12 32 03	36 39	121 14	4.1	c
Nov. 22	16 43 58	36.6	121.3	4.2	d
Dec. 1	14 11 25	36 52	121 36	4.4	b
1957					
Mar. 22	19 44 21	37 40	122 29	5.3	a
Mar. 22	23 14 35	37 39	122 27	4.4	a
Mar. 23	00 26 55	37 39	122 29	4.0	a
Mar. 23	08 13 48	37 42	122 31	4.2	a
Sept. 28	21 04 39	36 36	121 14	4.5	b
Oct. 31	20 13 07	37 21	122 13	4.1	a

* Geographic limits: Latitude 36° 30′ N to 38° 30′ N, Longitude 121° 00′ W to 123° 30′ W. (See figure 1.)

area, while other, much more energetic shocks centered in rural areas receive only passing mention in the historic record. Also, as the years pass, areas which formerly were nearly uninhabited become densely settled. Building practices change from decade to decade. A major earthquake such as that of 1906 will demolish many structures of poor design and construction, and, on the average, the replacement structures will be much more able to withstand future shocks of similar magnitude. These and other equally important factors make exceedingly difficult the task of finding some sort of pattern in the written record of past earthquakes which can be used as a possible guide to the future.

Despite these very real and important limitations on the significance of such a list of earthquakes as the foregoing, the historic record is the best we have prior to 1927. In that year routine seismographic recording was begun in southern California, and the Palo Alto station, with modern equipment, was added to the northern California network. This was the first station added to the northern chain since the establishment of Berkeley and Mount Hamilton in 1887.

The years 1848 to 1850 marked the beginning of a great increase in the population of California and also in the publication of local newspapers. The historic record of earthquakes is therefore much more nearly complete for the years since 1850 than prior to that time. The list of strong earthquakes in the San Francisco Bay region (including the Monterey Bay area) that reached intensity VII includes 52 separate entries in the 107 years 1851-1957 (counting double shocks and swarms of aftershocks as one entry). Doubtless the two shocks of greatest energy release in that period where the Hayward earthquake of October 21, 1868 and the San Francisco earthquake of April 18, 1906; they also seem to stand as rather important milestones in the list of strong shocks. In the 18 years up to and including 1868, the list contains 12 entries, while in the 13 years 1869-81 there are no entries. In the 25 years up to and including 1906, the list contains 26 entries, while in the 47 years 1907-53 there are only 10 entries. From this, it would

seem that when moderately strong earthquakes occur in the San Francisco area over a period of years with a frequency approaching one a year, we are in nowise justified in concluding that the regional elastic strain is being gradually released; rather we should consider them as symptoms of a buildup in the regional strain which must sooner or later find its relief in a shock of major proportions like those of 1868 and 1906.

The four years 1954-57 have seen four strong shocks in the San Francisco Bay region. Whether or not these are the first of a series which will continue for a number of years and culminate in a major shock remains to be seen. The historic record is too short and too uncertain in its details for such a definite statement; a major earthquake could hit San Francisco before these lines reach the printer, or there might not be such a shock in the next hundred years.

The instrumental data have been improving markedly in quality and quantity in recent years. Since the beginning of 1942, instrumental (Richter) magnitudes are available for all shocks in northern California large enough to be located by seismographic triangulation. Estimates of seismic intensity continue to be of importance as a measure of the effects a given earthquake has on man and his works; on the other hand, use of the instrumental magnitude scale permits us to eliminate geographic accidents of occurrence when attempting to compare the tectonic significance of different earthquakes.

Table 1 lists all shocks, since January 1, 1942, of magnitude 4.0 or more, centered within the geographic limits given at the head of the table. The lower limit of magnitude is somewhat arbitrary, but is high enough so that it is very unlikely that any shocks with magnitude above that lower limit have been missed. Epicenters of these shocks are shown in figure 1.

Examination of the annual frequency of shocks of magnitude 4.0 and above does not reveal any particular trend with time. On the other hand, the five most energetic shocks listed in table 1 (magnitudes 5.2 to 5.5) correspond to the five entries since 1942 in the list of shocks which attained intensity VII.

The San Andreas fault and the Hayward fault have long been recognized as the two major active faults of the bay region. All the great earthquakes and many of the other strong shocks on record since 1800 have had their sources in movements on or near one or the other of these faults. From figure 1, however, it can be seen that considerable seismic activity takes place east of that section of the Hayward fault between Mount Hamilton and Berkeley, and west of the San Andreas fault from Monterey Bay south. The Coast Ranges of central California are laced with numerous recently active faults (Recent in the geologic sense) which have been recognized by geologists in the field. There has not been any known instance of surface fault breakage other than on the Hayward and San Andreas faults in the Bay area. It will not be possible to say definitely which of the other faults are presently active until such time as the matter is resolved either by improved seismographic coverage of the area (permitting more accurate locations of epicenters) or by surface breakage on one of them. From the seismographic evidence, it seems probable, but by no means certain, that both the Calaveras (or Sunol) fault and the Riggs Canyon fault are sources of minor earthquakes in the region east of San Francisco Bay. Present limits of accuracy of seismographic determinations of epicenters do not permit us to say that there are no other faults in the East Bay which have been active in recent years.

The recent improvements in seismographic coverage have permitted a gradual improvement in the quality and quantity of epicenter determinations, so that today in the region immediately around San Francisco Bay, most if not all shocks down to magnitude 2 can be located within a few miles. The following generalizations, which are evident in figure 1 with respect to shocks of magnitude 4.0 and over, are also valid for the same period of time (1942-57) with respect to shocks at least as small as magnitude 3.0:

(a) Between Castro Valley and Milpitas, the Hayward fault is not the source of minor earthquakes.

(b) From a point on the San Andreas fault northeast of Watsonville as far as Marin County, that fault is the source of minor earthquakes at only two spots: near Palo Alto, and between San Bruno and Bolinas. (There is no evidence from the records of the same period of time that would indicate any activity along the San Andreas fault from Marin County to southern Humboldt County, although the seismographic coverage of that area is poor compared with that of the Bay region.)

(c) That section of the San Andreas fault which includes the southeastern 20 miles of the 1906 fault break and some additional miles to the southeast, and that section of the Hayward fault lying immediately to the east, are the sources of at least half of the earthquakes in the part of central California covered by figure 1.

(d) The region between the Hayward and San Andreas faults, at least from San Jose to the north end of San Francisco Bay, acts as a rigid block, in that earthquakes do not appear to have their foci there. A minor exception was a tiny shock (magnitude 2.1) in December 1956, with epicenter near Yerba Buena Island. It is also interesting to note that the Townley-Allen catalogue mentions that many shocks were felt on Russian Hill in San Francisco in April 1905. If these shocks were actually centered close to Russian Hill, it would appear that the region between the two major faults may cease to act as a unit when the regional strain builds up close to that necessary to initiate a major movement on one of the bounding faults.

The science of seismology is still far from being able to offer specific predictions of earthquakes. Nevertheless, the written record, both historical and instrumental, tells us plainly that the San Francisco Bay region is one of continued seismic activity. Every shock of the severity of that of March 22, 1957, can do a real service by reminding us that far stronger shocks have occurred in the past, and by warning us that stronger shocks are sure to strike in the future. It behooves us to listen to these periodic warnings, and, as Bailey Willis used to say, "Build strong; build like a ship."

INTENSITY AND GROUND MOTION OF THE SAN FRANCISCO EARTHQUAKE OF MARCH 22, 1957

By William K. Cloud
U. S. Coast and Geodetic Survey

With Notes on Remeasurement of the Triangulation Net in the Vicinity of San Francisco

By C. A. Whitten
U. S. Coast and Geodetic Survey

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ABSTRACT

The main shock of the earthquakes that centered on the San Andreas fault near San Francisco on 22 March 1957 was felt over a land area of about 12,000 square miles and was of maximum Modified Mercalli scale intensity 7 near the epicenter. Instruments at twelve Coast and Geodetic Survey strong-motion seismograph stations operated by the shock registered maximum accelerations from 0.11 gravity at 7 miles from the epicenter down to 0.01 gravity at 40 miles. Duration of stronger accelerations was not over 5 seconds.

INTRODUCTION

The main shock on 22 Mareh 1957, near San Franeiseo, was not a major earthquake, but it was strong enough and was so loeated as to yield some of the best strong-motion data obtained to date by the Seismologieal Field Survey, Coast and Geodetie Survey, of the United States Department of Commeree. Within 40 miles of the epicenter reeords were obtained from 12 of 13 first-elass strong-motion seismograph stations.* The shoek also resulted in a wealth of effeets data for use as a basis in rating intensity.

INTENSITY DISTRIBUTION

In 1906, intensity of the 18 April earthquake was governed to a large extent by foundation material, espeeially in San Francisco (Lawson, 1908, Atlas maps nos. 17, 19). The 22 Mareh 1957 earthquake revealed no sueh widespread pattern. Throughout San Franeiseo and the area adjaeent to the south the prevailing maximum intensity based on eriteria of the Modified Merealli seale (Wood and Neumann, 1931) was 6. That is, the general pattern of effects included eraeked plaster, broken dishes, fallen knickknacks, and shifted furniture. A limited number of small areas of intensity 7 near the epicenter were perhaps caused by loealized soil eonditions, but these formed no general pattern. To illustrate: eaving of banks at the south end of Lake Merced resulted from instability of saturated soils at the water's edge.

Figure 1 shows intensity distribution to the seale and detail warranted by the results. In the figure, between the so-called isoseismal lines, prevailing maximum intensities are indieated by Roman numerals IV, V, VI, ete. Local areas where intensity exeeeded the prevailing maximum are indicated by Arabie numerals 5, 6, etc. From the figure it is estimated that the shoek was felt over a land area of roughly 12,000 square miles. The potential felt area was probably 24,000 square miles, but half lay in the Paeifie Ocean.

STRONG-MOTION RESULTS

Although the 22 Mareh 1957 main shoek was not a major earthquake, the fact that 13 strong-motion seismograph stations were near the epieenter enhanced its seientific value. These stations were at the approximate locations shown in figure 2.

Seismograms were obtained from instruments at all stations except Berkeley. Motion of the roek foundation at Berkeley was apparently too weak to trigger the strong-motion seismograph into operation. A composite view of the records obtained at various distanees and at various elevations in structures is afforded by figure 3. In the figure attention is invited to:

(a) The attenuation of ground-level acceleration with distanee—from 11 percent gravity at 7 miles to 1 percent gravity at 40 miles.

(b) The short duration of stronger accelerations—about 5 seeonds.

(c) The magnifieation of horizontal aeeelerations in upper floors of buildings—a faetor of 3 in buildings B and C.

(d) The magnifieation of vertieal aeeelerations in upper floors of buildings—a faetor of 3 in building B; 5 in building C. This is one of the most interesting features of the reeords, and one deserving eonsiderable thought by engineers.

(e) The simple charaeter of the displaeement reeord obtained in building A.

Table 1. Maximum accelerations recorded at 12 strong-motion seismograph stations.

Component Direction	MAXIMUM ACCELERATION	
	Amplitude (% gravity)	Period (seconds)
Golden Gate Park—Ground Level— 7 miles from epicenter		
Vertical	6	0.1
N 10° E	11	0.2
S 80° E	13	0.2
San Francisco, Building A—Basement— 9 miles from epicenter		
Vertical	5	0.3
S 9° E	10	0.3
S 81° W	7	0.2
San Francisco, Building B—Basement— 10 miles from epicenter		
Vertical	4	0.2
S 9° E	5	0.2
N 81° E	5	0.3
Eleventh floor		
Vertical	10	0.2
N 81° E	5	0.2
S 9° E	6	0.3
Fifteenth floor		
Vertical	12	0.2
S 9° E	9	0.3
N 81° E	14	0.3
San Francisco, Building C—Basement— 10 miles from epicenter		
Vertical	3	0.2
N 45° W	5	0.2+1.1
S 45° W	5	0.2
Fourteenth floor		
Vertical	17	0.2
S 45° W	18	0.7+1.4
N 45° W	16	1.4
Oakland, Building D—Basement— 15 miles from epicenter		
Vertical	2	0.1
N 26° E	5	0.2
S 64° E	3	0.2+1.5
Sixteenth floor		
Vertical	11	0.2
N 26° E	13 and 6	0.2 and 1.20
S 64° E	7 and 3	0.3 and 1.5
Martinez, Suisun Bay Bridge—Pier— 33 miles from epicenter		
Vertical	0.3	0.2
N 59° E	3	0.5
S 31° E	5	0.2+1.8
San Jose, Building E—Basement— 40 miles from epicenter		
Vertical	0.3	0.2
N 59° E	0.8	0.3
S 31° E	0.8	0.4
Thirteenth floor		
Vertical	1	0.2
N 59° E	2	0.6
S 31° E	1	0.3

* First-class strong-motion seismograph stations are equipped with magnetically damped precision pendulums of one or more of the following types. Recording is by means of optical levers on photographic paper.

Types of pendulums

Type	Period	Average values of Static magnification	Damping ratio
Survey accelerometer	0.06	125	10
Carder displacement meter	2.5	Unity	10
Survey displacement meter	10	Unity	10

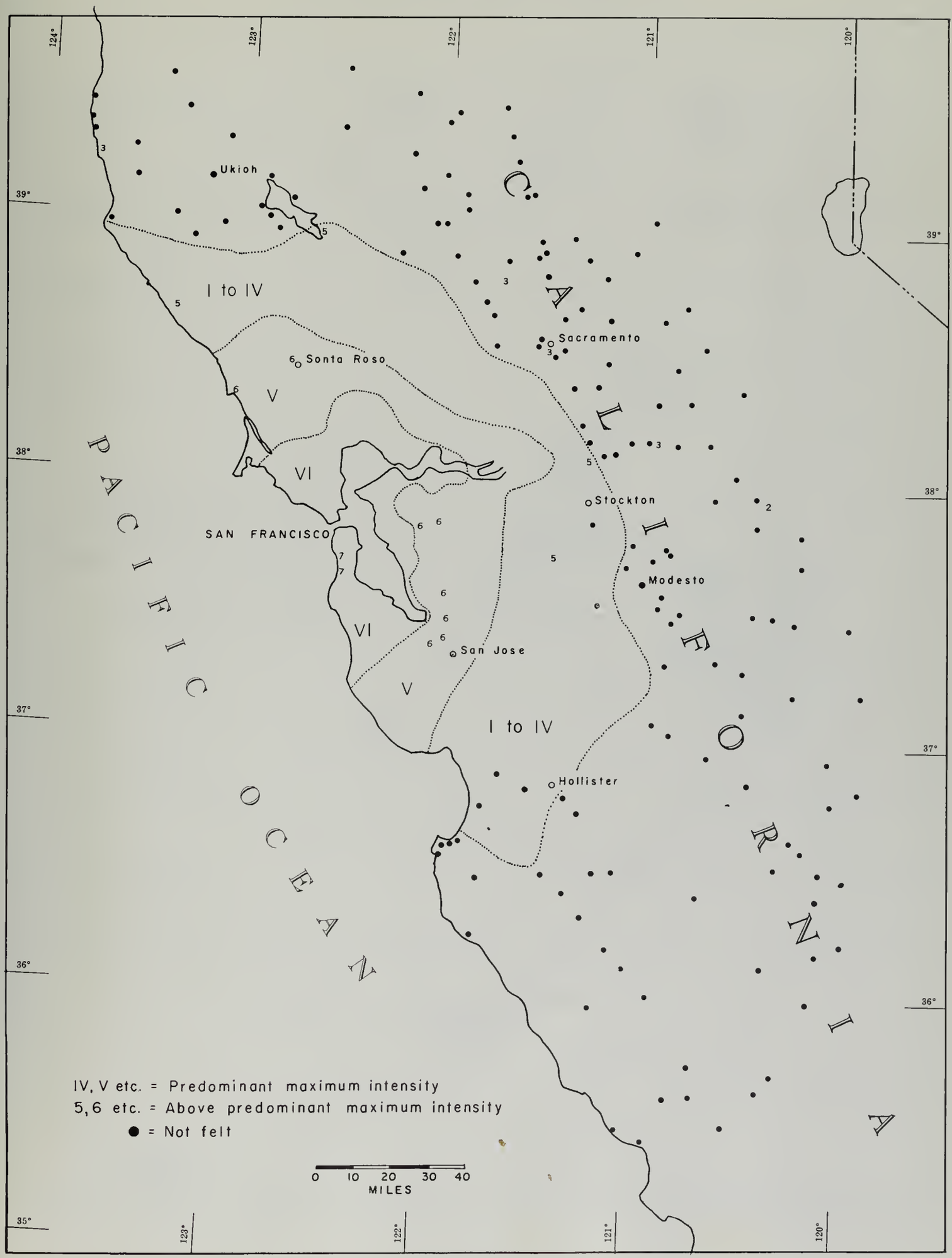

FIGURE 1. Isoseismal map of 22 March 1957 earthquake.

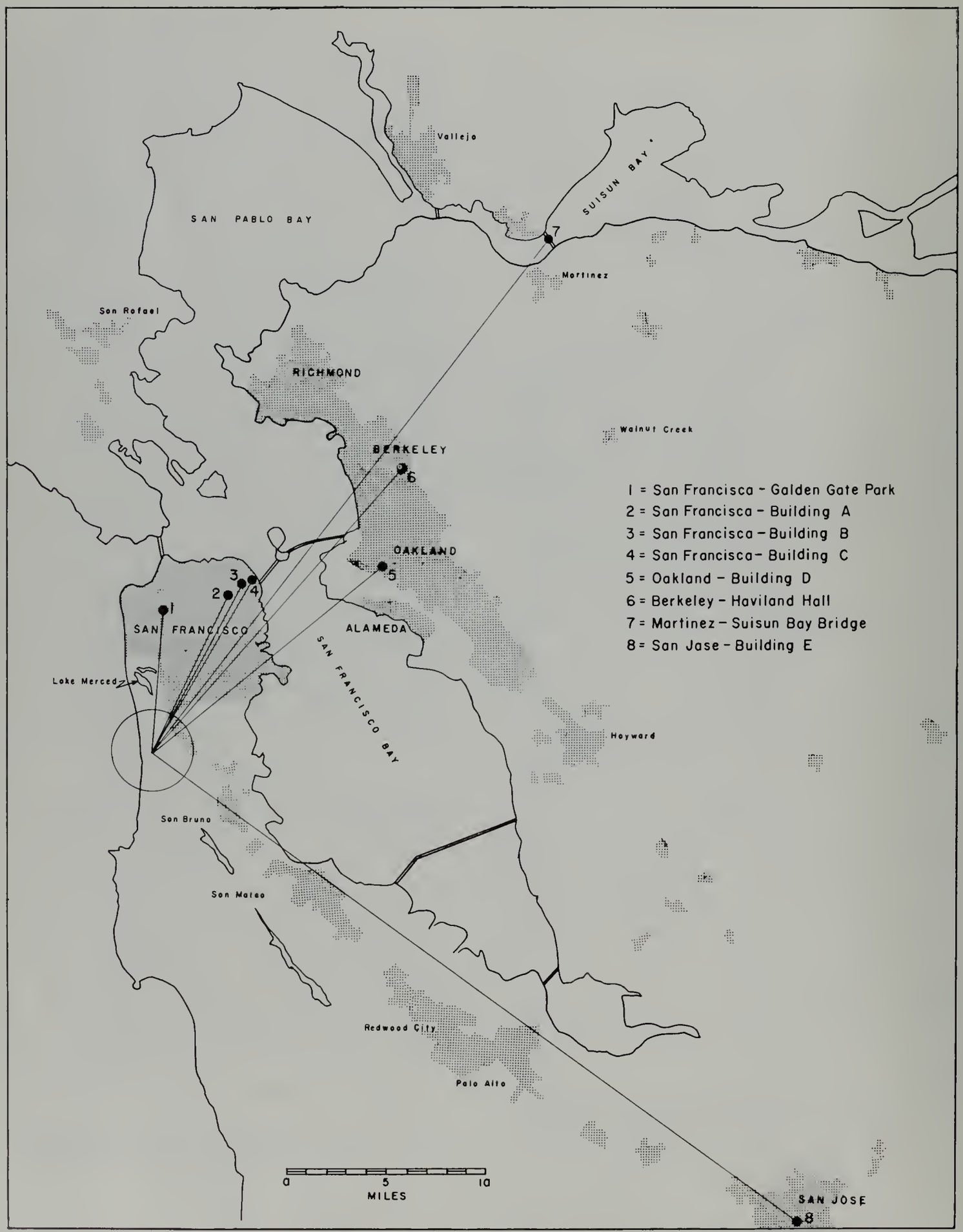

FIGURE 2. Location of strong-motion seismograph stations in the San Francisco Bay area relative to 22 March 1957 earthquake epicenter.

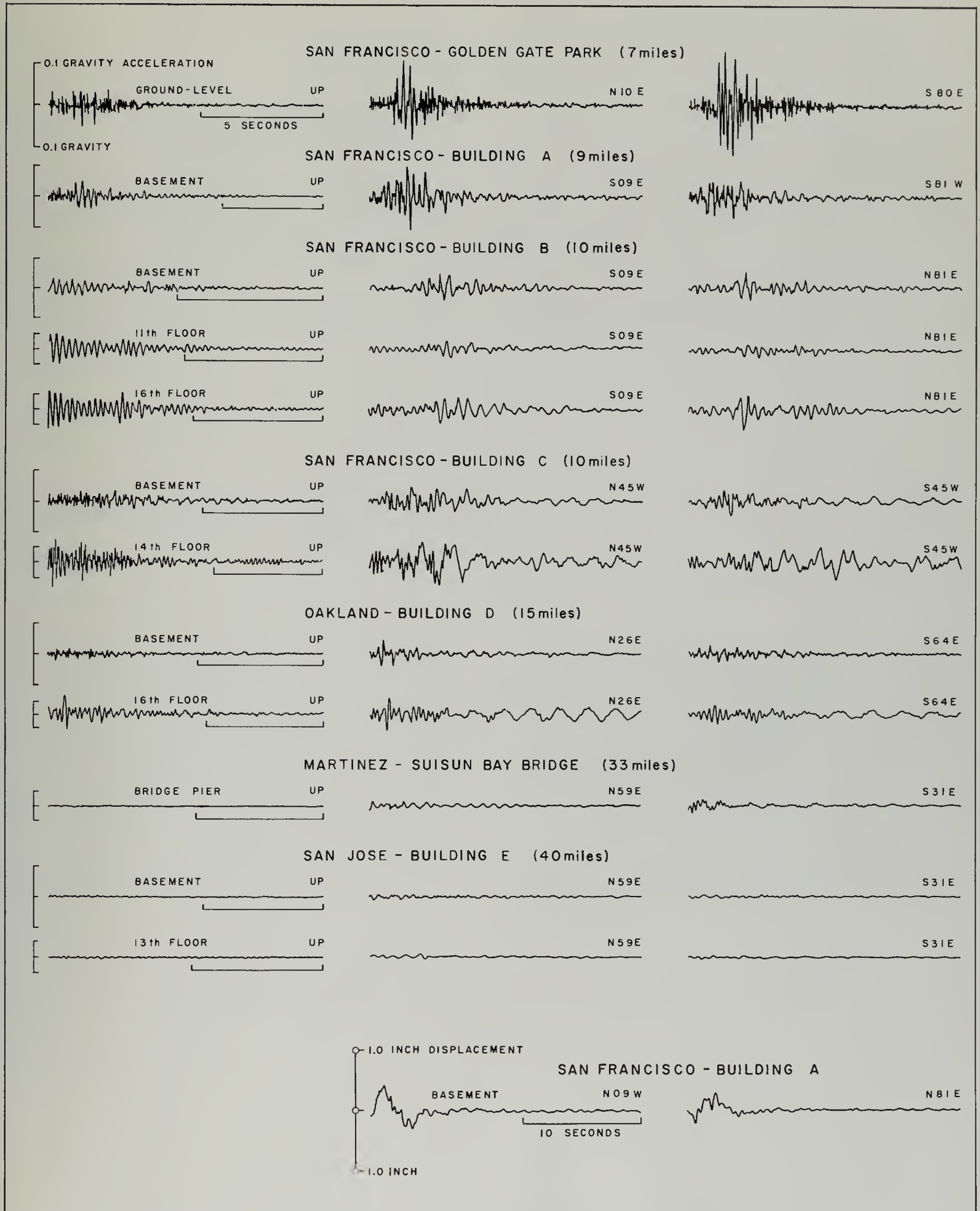

FIGURE 3. U.S. Coast and Geodetic Survey strong-motion seismograms of the 22 March 1957 main shock at 11:44:21 P.S.T.

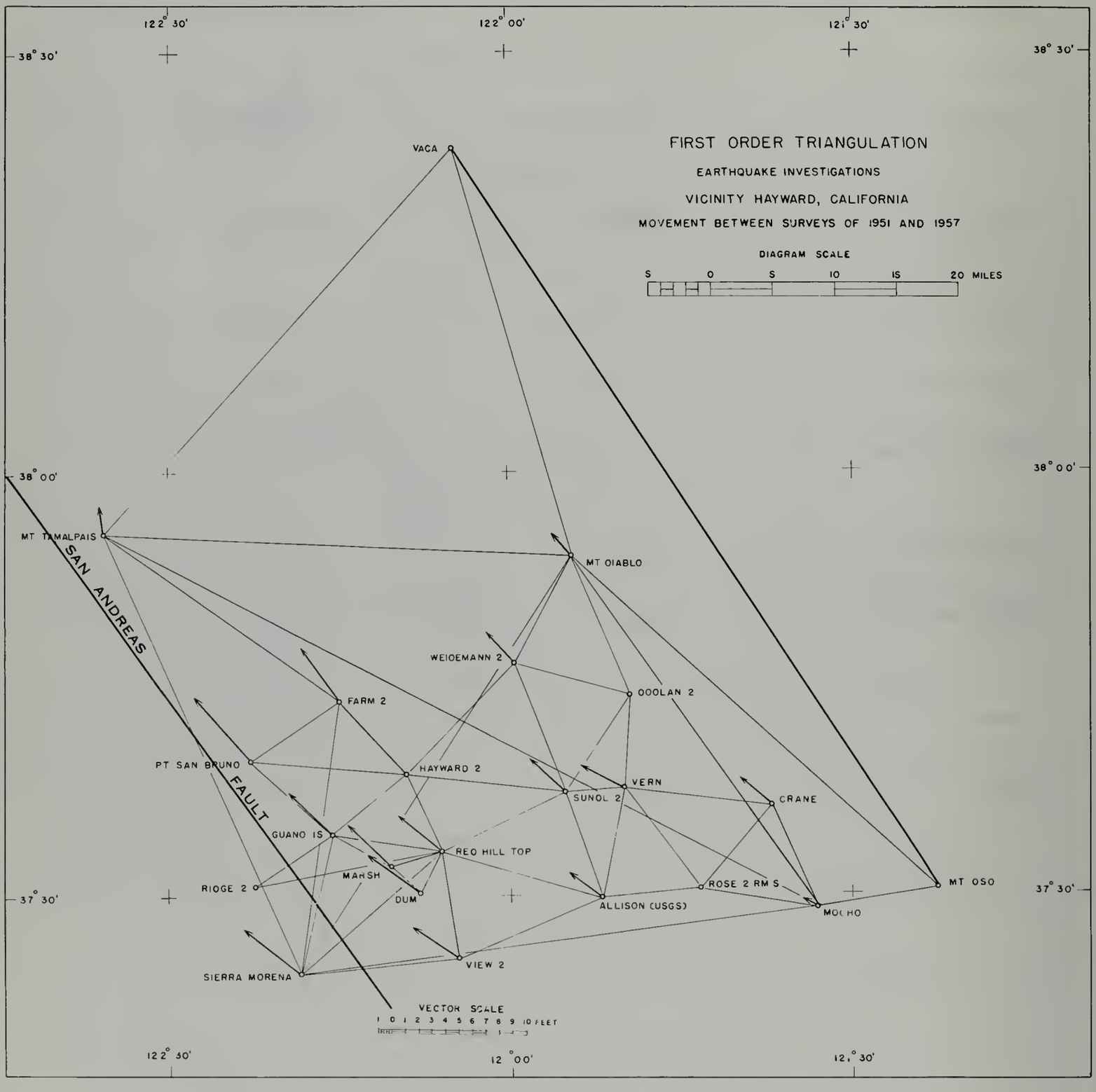

FIGURE 4. First-order triangulation, showing movement between surveys of 1951 and 1957.

To supplement figure 3 brief descriptions of the stations are given in the following paragraphs. To further supplement figure 3, table 1 lists maximum single-component accelerations scaled directly from the original seismograms. For more complete analyses of the seismograms, readers are referred to a companion paper in this Special Report entitled *Response Spectrum Analysis,* by D. E. Hudson and G. W. Housner.

Golden Gate Park Station—7 miles from epicenter. Reinforced-concrete vault. Rectangular, 10 feet by 10 feet. Vault rests on rock (Franciscan chert). No damage.

San Francisco, Building A—9 miles from epicenter. Six-story reinforced-concrete building with basement. Rectangular, 110 feet by 375 feet. Foundation—spread footings on unconsolidated sand. Minor plaster damage.

San Francisco, Building B—10 miles from epicenter. Fifteen-story steel-frame building with basement. Rectangular, 60 feet by 68 feet. Foundation—spread footings on deep sand and clay. Minor plaster damage.

San Francisco, Building C—10 miles from epicenter. Ten-story steel-frame building with full basement and tower; equivalent to 14 stories. E-shaped, with outline dimensions of 210 feet by 275 feet. Foundation—piling driven to an average depth of 125 feet into fill, mud, and clay. Site formerly part of San Francisco Bay. Considerable partition damage and a number of windows broken.

Oakland, Building D—15 miles from epicenter. Sixteen-story steel-frame building with basement, set-back walls, mezzanine, and cupola. Rectangular, 125 feet by 175 feet. Foundation—concrete mat on deep unconsolidated sediments. Minor plaster damage.

Martinez, Suisun Bay Bridge—33 miles from epicenter. One hundred seventy-four-foot reinforced-concrete bridge pier. Rectangular, 20 feet by 55 feet at bottom; 20 feet by 49 feet at top. Foundation—shale. No damage.

San Jose, Building E—40 miles from epicenter. Thirteen-story reinforced-concrete building with basement and cupola. Rectangular, 124 feet by 132 feet. Foundation—piling driven into unconsolidated clay and sand. No damage.

NOTES ON REMEASUREMENT OF TRIANGULATION NET IN THE VICINITY OF SAN FRANCISCO

By C. A. Whitten
July 16, 1958

After the San Francisco earthquake of March 22, 1957, the network of triangulation points originally observed in 1951 was reobserved. This net is composed of points 6 to 8 miles apart almost filling the area between Mount Tamalpais, Sierra Morena, Mount Diablo, and Mocho.

Figure 4 shows the shift in position as indicated by a comparison of two independent adjustments, using the line between Mount Oso and Vaca as a fixed base. The vectors show the same systematic movement as disclosed by previous resurveys. In the field, there does not appear to be any sharp break or discontinuity of vectors such as would be expected if there had been any large horizontal displacement along any of the fault lines.

A word of caution needs to be given concerning the interpretation of these vectors. The pattern suggests the possibility of clockwise rotation about the base line. Adverse atmospheric conditions during either survey could produce these effects. To illustrate, a 2-second azimuth change on the base line would show a false shift of 3 feet at Sierra Morena. Check angles which were measured at each end of the base indicated that adverse conditions did not exist, at least not to the extent of producing a false shift of 5 feet. Therefore, it can be concluded that a major portion of the indicated displacement is real, but possibly not all of it. For example, computations indicate a probable error of position determination at Sierra Morena of the order of 1 foot.

SEISMOGRAPHIC RESULTS FROM THE 1957 SAN FRANCISICO EARTHQUAKES

By Don Tocher, Seismologist
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Seismograph Station

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ABSTRACT

The San Francisco earthquake of March 22, 1957, was preceded by eight identifiable foreshocks, the earliest about 3 hours before the main shock. Aftershocks continued into 1958, and, because of their proximity to residential areas in and south of San Francisco, evoked rather more concern in the press than similar recent aftershock series in northern California. Epicenter of the main shock was 37° 40′ N, 122° 29′ W; origin time 19:44:21.0 GCT (11:44:21.0 P.S.T.); magnitude 5.3. This location is in the San Andreas rift zone near Mussel Rock, and is consistent with the observed distribution of intensities.

Epicenters of the aftershocks which were well recorded lie in a zone which is elongated in the direction of the San Andreas rift zone, and approximately bisected by it. No breakage at the surface was observed in the rift zone, although there were landslides and slumps on the steep coastal cliffs between Mussel Rock and the southern edge of San Francisco.

The main shock was not large enough to yield a complete fault-plane solution based on first motions at stations at large distances. However, the first motions at nearby stations are not consistent with right-lateral strike-slip movement on the San Andreas fault, suggesting instead movement of the continental side of the fault upward relative to the Pacific side.

ACKNOWLEDGEMENTS

I am indebted to the directors of many seismographic stations for making available the seismograms which constituted the basie data of this paper. The assistanee of Mr. Thomas Tureotte in measuring times and amplitudes and eomputing foeal eoordinates of the small aftershocks, and of Father William V. Stauder, S.J., in measuring arrival times and eomputing station distances and azimuths for the main shoek is gratefully acknowledged.

INTRODUCTION

The region of the epieenter of the San Franeiseo earthquake of Mareh 22, 1957, has been the loeus of eonsiderable seismie aetivity in the past, yet there was nothing in the seismie reeord prior to Mareh 22 to give any warning of the main shock of that date. Earthquakes between January 1, 1955, and Mareh 21, 1957, with epieenters near that of March 22, 1957, are listed in table 1; the list is representative of the normal level of minor

Table 1. Earthquakes on the San Francisco peninsula north of San Mateo, January 1, 1955, to March 21, 1957

Date	Origin time GCT	Latitude and longitude	Magnitude	Remarks
Feb. 14, 1955	20-24-05	37°43′N 122°32′W	2.0	
Nov. 22, 1955	12-31-47	37°36′N 122°26′W	2.2	Felt in San Francisco.
Dec. 1, 1955	04-46-12	37°37′N 122°31′W	2.4	Felt in San Mateo.
Dec. 23, 1955	12-40-33	37°37′N 122°27′W	2.6	Felt in Pedro Valley. Smaller shocks on Dec. 19, 24, 25.
Jan. 9, 1956	11-11-56	37°40′N 122°32′W	2.4	Felt in Daly City, Colma, and San Francisco.
Jan. 22, 1956	02-13-23	37°41′N 122°28′W	2.1	
Sept. 17, 1956	19-39-02	37°41′N 122°28′W	2.0	

seismie activity prevailing in this limited region. The strongest shoek eentered in the northern part of the San Franeiseo peninsula between the earthquakes of April 18, 1906, and Mareh 22, 1957, apparently was that of October 2, 1934. Byerly (1939) reported 0 = 20-20-37.8 GCT, epicenter 37° 41.9′ N., 122° 27.9′ W. Magnitude was 4.5, with an aftershoek 10 minntes later of magnitude 4.2. Damage from these 1934 earthquakes was negligible, and the area over which they were felt was considerably smaller than for the 1957 earthquake. Other earthquakes as strong or stronger than this have oeeurred in eentral California sinee 1906, but none within 20 miles of the eity of San Franeisco. It is safe to say that the earthquake of Mareh 22, 1957, was more severe in San Franeisco than any shock sinee 1906.

FOCAL COORDINATES AND ORIGIN TIMES

The foeal depth of a shallow earthquake whieh has its focus in the earth's crust is generally determinable with reasonable precision only if the epicentral distanee of at least one seismographie station does not greatly exeeed

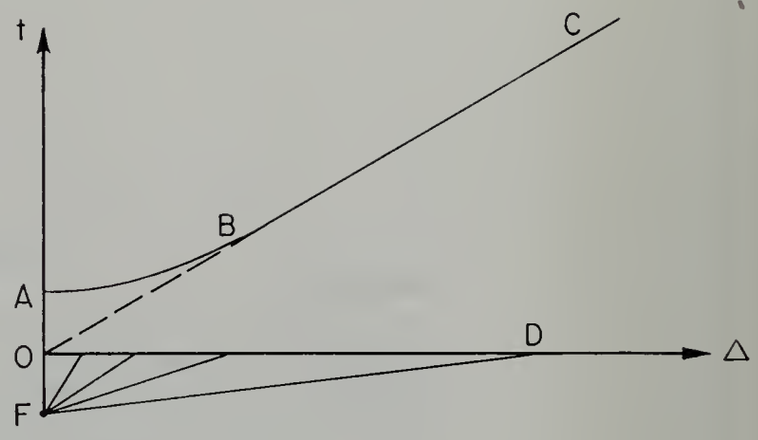

FIGURE 1. Travel-time eurve and ray paths of $\overline{P}$.

the depth of focus. The travel-time eurve of the wave whieh travels direetly from foeus to reeording stations is very nearly a straight line exeept for the portion elose to the epieenter. Sueh a travel-time eurve is shown in figure 1, in whieh Δ is distanee along the earth's surfaee from epieenter to station, and t is the travel-time of the direct wave. Ray paths from foeus to points on the surface are shown in the lower part of the figure, in whieh the Δ-axis represents the surfaee of the earth. The travel-time of the direct wave is given by

$$t = d/v = \sqrt{\Delta^2 + h^2}/v \qquad (1)$$

where d is the foeal distanee, h the depth of foeus, and v the speed in the upper layer of the earth's erust. At distanees at whieh Δ is large with respect to h, (1) is elosely approximated by $t = \Delta/v$; this portion is represented by the section BC in figure 1. At these large distanees, the epieentral distanee Δ_D (= OD) to a station at D is almost identieal to the foeal distanee FD. If the time of arrival of the direct wave at D is t_D, the time of occurrence at the focus is $t_D - FD/v = t_D - \Delta/v$. Thus the prolongation of the straight-line portion BC of the travel-time eurve euts the time axis at the time of oeeurrenee of the earthquake. Observations from several stations at distances on the BC section of the travel-time eurve will serve to determine the epieenter and time of oeeurrenee of the shoek and v, whieh is the reciproeal of the slope of the BC portion of the eurve. However, h ean be eomputed only if there is an observation on the AB portion of the eurve. In this event, d = vt, where t is arrival time minus time of oeeurrenee. Δ ean be eomputed from the established position of the epieenter and the known loeation of the nearby station, and

$$h = \sqrt{d^2 - \Delta^2}. \qquad (2)$$

The effect on h of an uneertainty in Δ ean be seen from

$$\frac{|\partial h|}{|\partial \Delta|} = \frac{\Delta}{\sqrt{d^2 - \Delta^2}} = \frac{\Delta}{h}. \qquad (3)$$

For a shock 10 kilometers deep, an uneertainty of 2 kilometers in the epieenter loeation would introduee an uncertainty of 10 kilometers in the eomputed value of h

if the nearest station were 50 kilometers from the epicenter, but an uncertainty of only 2 kilometers if the nearest station were 10 kilometers from the epicenter.

The San Francisco earthquakes of 1957 were very favorably situated for determining focal depths. Three stations, San Francisco, Berkeley, and Palo Alto, were all within 40 to 45 kilometers of the epicenters; the average epicentral distance to the San Francisco station was about 10 kilometers. From previous studies of seismic velocities and crustal structure in central California (Byerly, 1939; Tocher, 1955), the first arrival to be expected at these three stations from foci in the upper 10 or 12 kilometers of the crust is the direct wave traveling with a speed of 5.6 km/sec (neglecting the lesser speed through a thin veneer of sedimentary rock at the surface).

In determining the origin times and focal coordinates (latitude, longitude, and depth of the focus) of well-recorded shocks of the series, the following procedure was used:

1. Origin time t_o was determined from

$$t_o = t_p - (t_s - t_p)/0.732 = t_p - t, \qquad (4)$$

where t_p is arrival time of the direct P-wave and t_s arrival time of the direct S-wave. The divisor 0.732 comes from classical elastic theory, and depends on the following assumptions:

a. The P- and S-waves originate at the same time and place.

b. Poisson's ratio is one fourth in the rock between focus and station.

As long as this process is applied only to readings from stations at which $(t_s - t_p)$ does not exceed a few seconds, a small deviation in the elastic properties of the rock from assumption b will introduce only a very small error into the value of t_o. P and S arrivals at Berkeley and San Francisco were both quite sharp for a number of the earthquakes, permitting two independent determinations of t_o of these shocks. For most of the shocks, the two values differed by 0.2 of a second or less; for none did this difference exceed 0.3 of a second. Origin time computed from the San Francisco records was adopted as the t_o of shocks for which good measurements of both P and S were available; otherwise the adopted origin time was that computed from the Berkeley records.

2. Travel-times of the direct P-wave to San Francisco, Berkeley, and Palo Alto were computed from $t = t_p - t_o$.

3. Taking the origin of a set of Cartesian coordinates in the Berkeley station, with x-axis positive eastward, y-axis positive southward, and z-axis positive downward, the coordinates of each station in kilometers were computed by the method of Mean-Latitude Sailing as described by Richter (1943):

Berkeley	$x_1 = 0$	$y_1 = 0$	$z_1 = 0$
San Francisco	$x_2 = -18.5$	$y_2 = 10.9$	$x_2 = 0$
Palo Alto	$x_3 = 7.1$	$y_3 = 50.3$	$z_3 = 0$

The distance d between each station and the focus is then give by

$$d_n = [(X - x_n)^2 + (Y - y_n)^2 + (Z - z_n)]^{1/2} \qquad (5)$$

where X, Y, and Z are the coordinates of the focus.

4. For each well-recorded shock in the series, X, Y, and Z were obtained by solving the set of three simultaneous linear equations:

$$t_n = d_n/v, \qquad n = 1, 2, 3. \qquad (6)$$

During part of March 22, and intermittently during the next few weeks, the time-marking system at the San Francisco station failed to function properly. To determine the coordinates of shocks recorded during those periods, the adopted origin time was that computed by (4) from the Berkeley records, and the travel time to San Francisco was obtained from $t_{SF} = (t_s - t_p)_{SF}/0.732$, inasmuch as the known drum rate there permitted measurement of the S-P interval even though the absolute time of P was not available. The records of the main shock at all nearby stations blanked out shortly after the arrival of the first P-wave due to rapid motion of the light spot on the photographic recording paper. For this reason, no (S-P) interval could be measured; in addition, the San Francisco time-marking system was not operating. Therefore the epicenter of the main shock was determined by comparison of the arrival time of the first recorded P-wave at Berkeley, Palo Alto, and Mount Hamilton with the corresponding times of the five largest foreshocks. With no absolute arrival time available at San Francisco, the focal depth of the main shock is not determinable. Focal depths of the five largest foreshocks were all between 7 and 11 kilometers, however, perhaps suggesting that the focus of the main shock was also in that range of depths.

Table 2 lists origin times and focal coordinates for the larger shocks of the 1957 series. It is complete for foreshocks down to magnitude 2.2, and, except for the first 8 minutes after the main shock, is complete for aftershocks down to magnitude 3.0. At least two additional aftershocks of magnitude above 3 occurred during that interval, but accurate times could not be measured because of continuing arrivals from the main shock. The last aftershock with magnitude as large as 3 occurred on June 13, 1957. All well-located epicenters are plotted on the map of figure 2; identifying symbols on the map correspond to the first column of table 2.

The accuracy of the focal coordinates given in table 2 cannot be measured by the usual statistical methods, inasmuch as the three coordinates are obtained as the exact solution of three simultaneous equations. However, the agreement in the origin times computed independently from the (S-P) intervals at Berkeley and San Francisco implies that the error in a single arrival time measurement does not exceed about 0.2 of a second. From this, we can estimate that the uncertainty in a single epicenter location introduced by errors in timing does not exceed about 2 kilometers. The uncertainty in a single focal depth determination depends both upon the depth itself and upon the epicentral distance to the nearest station (San Francisco). Focal depths of the deeper shocks are about as accurate as the epicenter locations, while the uncertainty is somewhat greater for the shallower shocks, especially those farthest from San Francisco.

P TRAVEL-TIMES FOR THE MAIN SHOCK

Because of the relatively small amount of energy released in the main shock of March 22, 1957, few records

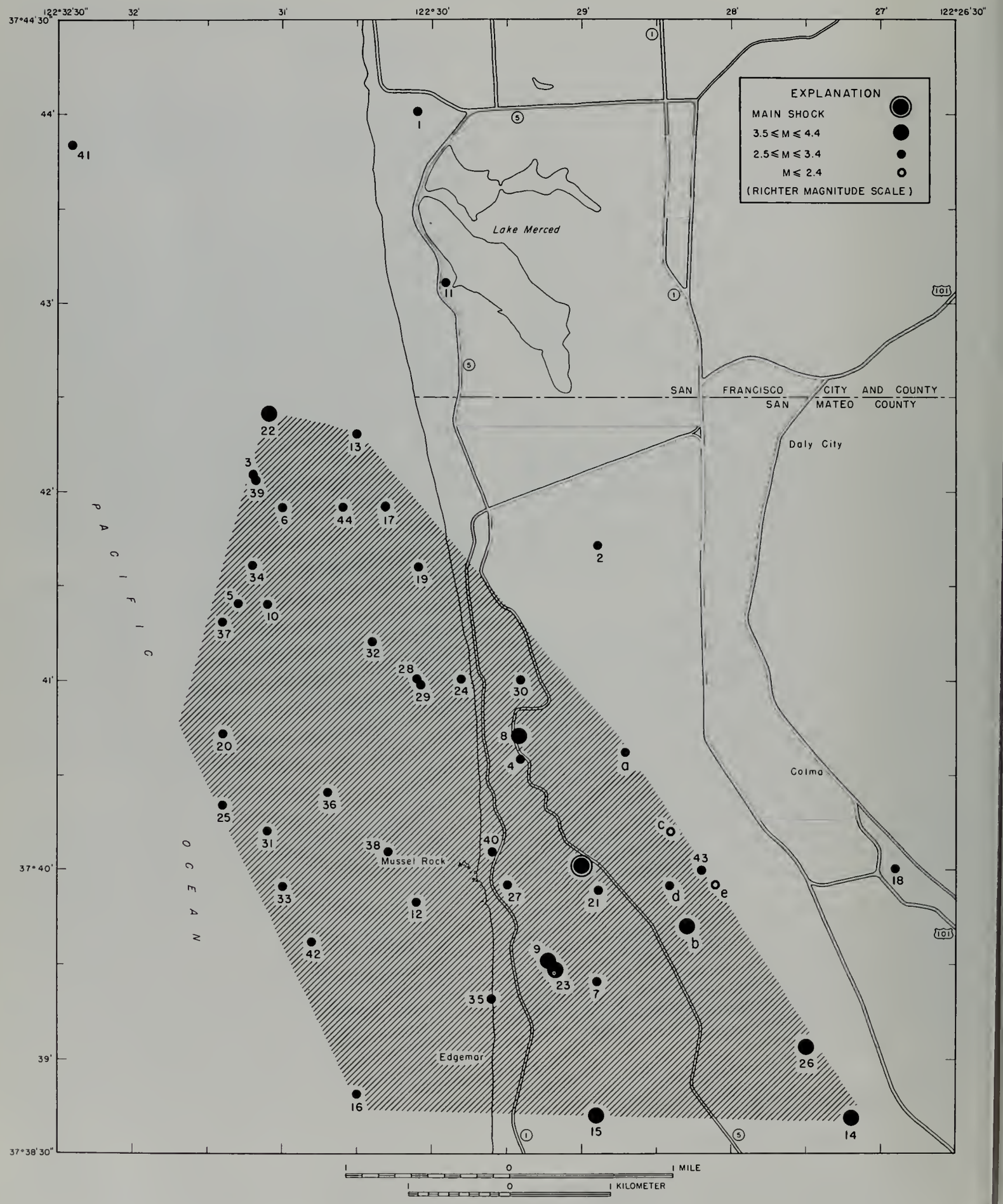

FIGURE 2. Epicenters of the larger aftershocks.

Table 2. Origin times and focal coordinates of the larger earthquakes of the 1957 San Francisco series

No.	Date 1957	Origin time (GCT)	Magnitude	Lat. N	Long. W	Focal depth (km)
				37°	122°	
a	March 22	16-38-00.7	2.7	40.6′	28.7′	10.4
b		18-48-23.0	3.8	39.7′	28.3′	7.4
c		18-52-27.8	2.2	40.2′	28.4′	9.6
d		19-04-19.8	2.6	39.9′	28.4′	7.9
e		19-19-14.7	2.3	39.9′	28.1′	9.0
Main		19-44-21.0	5.3	40′	29′	--
1		19-52-30.4	3.4	44.0′	30.1′	13.8
2		19-56-33.6	2.7	41.7′	28.9′	10.7
3		20-00-26.4	3.1	42.1′	31.2′	8.2
4		20-03-48.2	3.1	40.6′	29.4′	10.1
5		20-16-40.8	3.0	41.4′	31.3′	6.6
6		20-32-16.0	3.0	41.9′	31.0′	8.0
7		20-59-39.4	2.7	39.4′	28.9′	10.2
8		21-07-46.8	3.6	40.7′	29.4′	6.7
9		21-18-29.4	3.8	39.5′	29.2′	7.4
10		21-29-43.1	2.7	41.4′	31.1′	4.2
11		21-37-53.5	2.7	43.1′	29.9′	10.5
12		22-26-30.1	2.8	39.8′	30.1′	6.9
13		22-39-57.7	2.8	42.3′	30.5′	7.6
14		23-14-35.0	4.4	38.7′	27.2′	5.0
15	March 23	00-26-55.1	4.0	38.7′	28.9′	4.8
16		01-45-30.2	2.9	38.8′	30.5′	7.5
17		02-48-07.9	3.4	41.9′	30.3′	8.7
18		03-28-53.2	3.2	40.0′	26.9′	9.4
19		05-42-13.3	3.2	41.6′	30.1′	8.3
20		06-14-23.5	2.7	40.7′	31.4′	9.8
21		07-53-59.6	3.0	39.9′	28.9′	8.9
22		08-13-48.3	4.2	42.4′	31.1′	9.6
23		12-54-32.5	3.8	39.5′	29.2′	7.4
24		16-56-31.9	2.8	41.0′	29.8′	5.8
25		17-36-13.7	3.3	40.3′	31.4′	3.7
26		22-48-00.5	3.5	39.1′	27.5′	3.6
27	March 24	00-35-27.6	3.1	39.9′	29.5′	6.1
28		03-35-59.5	3.2	41.0′	30.1′	9.7
29		03-52-00.3	2.8	41.0′	30.1′	9.7
30		06-26-50.6	2.7	41.0′	29.4′	10.1
31		19-11-16.4	2.8	40.2′	31.1′	1.3
32		19-52-33.1	2.5	41.2′	30.4′	7.0
33	March 25	00-22-23.7	2.7	39.9′	31.0′	7.1
34		08-05-09.8	2.7	42.6′	31.2′	8.2
35		09-31-11.2	2.6	39.3′	29.6′	8.5
36	March 26	14-51-29.1	2.7	40.4′	30.7′	10.6
37		15-20-53.4	2.4	41.3′	31.4′	10.0
38	March 27	02-13-24.6	3.1	40.1′	30.3′	6.0
39		10-41-52.8	3.1	42.1′	31.2′	8.2
40	April 7	16 20-40.1	3.3	40.1′	29.6′	6.8
41	April 27	00-15-04.0	3.0	43.8′	32.4′	7.5
42	April 30	06-27-46.1	3.4	39.6′	30.8′	6.5
43	May 1	19-36-22.5	3.3	40.0′	28.2′	9.2
44	June 13	10-40-55.5	3.0	41.9′	30.6′	7.5

of it were written at stations outside North America. A distinct T-phase was observed at the Hawaiian Volcano Observatory ($\Delta = 31°$ ca.), but no body waves were recorded there. P was weakly recorded as far as College, Alaska ($\Delta = 31.1°$), Shawinigan Falls, Canada ($\Delta = 37.7°$), and possibly at Balboa Heights, Canal Zone ($\Delta = 48.1°$); in general, the beginning of P was rather uncertain at stations beyond about 20° from the epicenter.

Table 3 lists in the column headed "P-O, Obs." travel-times of the first detectable longitudinal waves to stations in western North America. These travel-times are measured from the adopted origin time of the shock —19-44-21.0 GCT. Epicentral distances and station azimuths were computed from the adopted epicenter—37° 40′ N, 122° 29′ W.

Table 3. P travel times and directions of first motion of the main shock

O = 19-44-21.0 GCT. 37°40′N, 122°29′W.

Station	Az. N°E	Δ km.	P — O (sec.) Obs.	P — O (sec.) Comp.	O — C sec.	First motion
San Francisco	012.6	12.1	_			NEc
Berkeley	040.9	30.1	5.5			NEc
Palo Alto	134.2	38.5	7.1			SEc
Santa Clara	126.7	58.8	11	10	1	
Mt. Hamilton	116.0	82.6	14.4	13.7	0.7	d
Ukiah	338.5	174.8	25.0	26.5	—1.5	d
Fresno	112.7	258.5	37.9	37.0	0.9	d
Mineral	014.4	307.1	43.3	43.1	0.2	SWd
Reno	050.0	311.9	46.2	43.7	2.5	d
Yerington	063.2	325.5	47.7	45.4	2.3	Wd
Shasta	001.4	336.3	45.7	46.7	—1.0	Sd
King Ranch	132.4	357.3	52.4	49.4	3.0	
Ferndale	334.5	357.8	49	49	0	
Fallon	058.2	380.5	56.2	52.3	3.9	
Arcata	338.9	382.1	52.4	52.5	—0.1	S
Tinemaha	100.8	383.1	56.1	52.6	3.5	d
Woody	123.9	391.5	53.6	53.6	0.0	d
Isabella	122.1	422.8	58.5	57.6	0.9	d
China Lake	115.2	482.2	67.6	65.0	2.6	d
Pasadena	135.1	551.3	75.4	73.6	1.8	(c)
Dalton	132.6	573.1	77.3	76.3	1.0	c
Eureka	067.6	602.8	81	80	1	d
Riverside	131.9	615.8	82.4	81.7	0.7	(d)
Big Bear	127.1	630.3	84.8	83.5	1.3	(d)
Palomar	132.2	699.4	93.4	92.1	1.3	d
Boulder City	105.3	707.1	96.6	93.1	3.5	(d)
Hayfield	125.3	759.7	100.2	99.7	0.5	
Barrett	133.7	765.7	100.9	100.4	0.5	
Corvallis	354.9	711.4	105.0	101.1	3.9	d
Salt Lake City	073.4	980.8	135.9	127.3	8.6	d
Seattle	000.0	1109.1	148.6	143.3	5.3	(d)
Victoria	356.4	1206.9	156.7	155.6	1.1	d
Butte	039.6	1236.9	162.8	159.3	3.5	
Bozeman	046.1	1298.7	172.3	167.0	5.3	d
Horseshoe Bay	356.7	1302.8	170.2	167.6	2.6	d
Boulder	076.1	1516.5	200	193	7	(d)
Rapid City	064.9	1763.2	222	225	—3	d

Computed values of (P-O) are based on the crustal structure determined for the San Francisco Bay area by Byerly (1939), and on a focal depth of 10 kilometers. This structure consists of an upper crustal layer 12 kilometers thick in which the speed of P-waves is 5.6 km/sec and a lower crustal layer 18 kilometers thick in which the speed is 6.7 km/sec, overlying the rock of the top of the mantle in which the speed is 8.0 km/sec. Under these conditions, the first wave to arrive at Berkeley, San Francisco, and Palo Alto is $\overline{P}$, which has traveled entirely in the upper layer; the first at Santa Clara and Mount Hamilton is P*, which has traveled mainly in the intermediate layer; at all other stations (with the possible exception of Rapid City), the first arrival is P_n traveling in the upper part of the mantle. At Rapid City ($\Delta = 15.9°$) the anomaly is —3 seconds, suggesting that the first arrival has traveled through a deeper, higher speed region of the mantle.

The anomalies listed in table 3 (column headed "O-C") are, of course, relative to the structure and focal depth involved in calculating the "computed" values of (P-O). A focal depth of five kilometers instead of the 10 used in the calculations would algebrai-

cally reduce the P* anomalies by 0.5 of a second and the P_n anomalies by 0.7 of a second. In a very general way the P_n anomalies increase algebraically with increasing distance. This may be due to one or more of the following:

(a) The adopted velocity of 8.0 km/sec for the top of the mantle may be somewhat high for this region. Other studies in northern California have revealed slightly lower values of the P_n velocity, particularly when the earthquakes studied were centered in Humboldt County or off Cape Mendocino.

(b) The Mohorovicic Discontinuity on the average becomes deeper away from the Pacific Ocean, so that, in the parlance of the seismic prospector, we are shooting "down dip." Thus, the thicker the crustal layers are under a station, the larger the algebraic value of the anomaly will be. This thickening of the crust in central California reaches its maximum in the well-known root of the Sierra Nevada (Byerly, 1938), which introduces the rather large delays in arrivals at stations immediately east of the Sierra Nevada (Reno, Yerington, Fallon, Tinemaha, China Lake). The anomalies at King Ranch, Boulder City, Corvallis, Salt Lake City, Seattle, Butte, Bozeman, and Boulder all seem too large to be explained entirely in terms of a crust thicker than that under coastal California, although anomalies of similar size were noted at Corvallis and Seattle from the Fallon earthquakes of July 6 and August 24, 1954 (Toeher, 1955).

(c) Especially at the more distant stations, the first detectable motion of the ground on the seismograms is scarcely above the microseism level. Weaker arrivals in advance of those measured could have been missed.

The particular combination of anomalies at Corvallis (3.9 sec), Seattle (5.3 sec), and Victoria (1.1 sec) is quite similar to the corresponding values found for the Fallon, Nevada, earthquakes of July 6 and August 24, 1954 (Toeher, 1955). Relative to arrival times at Reno, and also computed against a P_n velocity of 8.0 km/sec, the average of the delays for the two Nevada shocks was 3.6 seconds at Corvallis, 5.5 seconds at Seattle, and 1.8 seconds at Victoria. All three stations are located west of the Cascade Range; Corvallis and Seattle are 80 to 100 km, and Victoria about 200 km, west of the axis of the range. If this pattern of anomalies is to be explained by a thicker crust under stations with higher anomalies, then the crust must be very thick immediately west of the Cascade Range (perhaps as much as twice as thick under the Seattle area as under the San Francisco Bay area). In addition, the crust must thin rapidly in the 125 km between Seattle and Victoria.

SHOCK MAGNITUDES

Richter (1935) has defined the magnitude of a shallow earthquake as the common logarithm of the maximum trace amplitude (in units of 0.001 mm) with which a standard Wood-Anderson torsion seismometer would record the earthquake at a distance of 100 km. The method since has been extended to permit determining magnitudes from the ground amplitudes and periods recorded on any type of instrument at large distances, but the original method remains the only practical one for small, nearby earthquakes. For rapid determination of magnitudes, Nordquist (1942) has designed a nomogram relating distances and trace amplitudes to the magnitude.

The main shock on March 22, 1957, caused every seismograph in the San Francisco Bay region to go off scale, so that all nearby records are useless for magnitude determination. Many of the standard torsion instruments operated by the Pasadena Seismological Laboratory in southern California wrote excellent records of the shock, however, and Richter (personal communication) has reported the magnitude as 5.3. For comparison, magnitudes of several other notable California and Nevada shocks are given below:

San Francisco, 1906	8¼
Santa Barbara, 1925	6¾
Long Beach, 1933	6¾
Arvin-Tehachapi, July 1952	7.6
Bakersfield, August 1952	5.8
Watsonville, April 1954	5.3
Fairview Peak, Nevada, December 1954	7.2
Eureka, California, December 1954	6.5
San Jose, September 1955	5.5
Walnut Creek, October 1955	5.4

Foreshocks and aftershocks of magnitude above about 2½ yielded records useful for magnitude determination on the Wood-Anderson seismograms from at least three stations (Berkeley, Mount Hamilton, Palo Alto), while two additional stations (Arcata and Mineral) provided records useful for this purpose from shocks of magnitude larger than about 3½. In computing magnitudes for these larger shocks, the following corrections were applied to the value obtained from records of an individual station:

Berkeley	+0.2
Arcata	+0.2
Mount Hamilton	+0.1
Palo Alto	−0.1
Mineral	−0.1

These values of the station corrections are those used in routine determinations of magnitudes of earthquakes in northern California, Nevada, and Oregon, and reflect differences of ground conditions and instrumental variations of each station from the mean of all stations. Examination of the magnitudes computed from records of each station revealed that the measured trace amplitudes at Berkeley yielded a value which, after the aforementioned correction was applied, was still 0.1 unit of magnitude lower than the mean value from all stations. Accordingly, a Berkeley station correction of +0.3 was used for the very small shocks for which magnitudes were necessarily determined from the records of less than three stations.

Table 4 lists origin times and magnitudes of all but the smallest shocks of the 1957-58 San Francisco series through May 14, 1958. Except for the first 10 minutes after the main shock, and the possible exception of shorter periods following the two or three largest aftershocks, table 4 includes all shocks of magnitude 2.0 and above.

STRAIN CHARACTERISTICS OF THE FOCAL REGION

The focal coordinates determined from seismographic data represent only that point at which fault breakage commences. Unless surface breakage is observed, the data available for a single earthquake do not reveal the area of the part of the fault plane that experienced slippage,

Table 4. Origin times and magnitudes of the March 22, 1957 earthquakes.

Date 1957	Origin time (GCT) h m s	Magnitude
Mar. 22	16-38-00.7	2.7
	18-48-10	2.7
	18-48-23.0	3.8
	18-52-27.8	2.2
	19-04-19.8	2.6
	19-19-14.7	2.3
	19-25-18	1.4
	19-33-15	1.6
	19-44-21.0	5.3
	19-48-22	2.8
	19-49.1	2.7
	19-50-16	3.2
	19-51-51	3.0
	19-52-30.4	3.4
	19-53.1	1.7
	19-53.6	2.3
	19-53-44	2.5
	19-54-26	2.0
	19-54-34	2.6
	19-54-57	1.9
	19-56-33.6	2.7
	19-57-36	2.2
	20-00-26.4	3.1
	20-03-10	2.3
	20-03-48.2	3.1
	20-05-15	2.5
	20-07.5	2.0
	20-07-41	2.2
	20-08-12	2.7
	20-11-37	2.2
	20-13.3	2.0
	20-15.6	2.0
	20-16-40.8	3.0
	20-18.6	2.6
	20-21-36	1.9
	20-22-17	2.4
	20-27.1	2.1
	20-28.5	2.5
	20-29-01	2.1
	20-32-16.0	3.0
	20-35-35	2.3
	20-37-05	1.9
	20-39-47	1.7
	20-41-23	2.1
	20-42-33	1.7
	20-45-19	1.7
	20-45.4	2.2
	20-59.0	1.6
	20-59-37.7	2.7
	21-01-29	2.0
	21-07-46.8	3.6
	21-10.0	1.7
	21-12.51	1.7
	21-14-18	2.0
	21-18-29.4	3.8
	21-26-31	1.7
	21-29-43.1	2.7
	21-32-00	2.6
	21-32-45	2.2
	21-34.8	1.6
	21-35-46	2.3
	21-37-53.5	2.7
	21-46-20	2.6
	21-52-22	2.0
	22-01-44	2.2
	22-26-30.1	2.8
	22-30-22	1.9
	22-39-57.7	2.8
	22-53-29	2.0
	23-01-45	1.7
	23-03-53	1.8
	23-14-35.0	4.4
Date 1957 (cont.)	Origin time (GCT) h m s	Magnitude
	23-22.1	1.7
	23-38.6	1.7
	23-50.5	1.7
	23-59.2	2.5
Mar. 23	00-02.1	2.2
	00-15-09	2.0
	00-26-55.1	4.0
	00-34-38	1.7
	01-03-22	2.2
	01-04-49	2.0
	01-07-05	1.6
	01-13-15	1.7
	01-15-33	2.4
	01-26-02	2.3
	01-28-57	2.0
	01-43-29	1.7
	01-45-30.2	2.9
	02-27-48	2.6
	02-34-11	2.2
	02-38-06	1.7
	02-48-07.9	3.4
	02-59.6	2.4
	03-00-15	1.9
	03-08-11	2.2
	03-09-43	1.6
	03-27-32	1.6
	03-28-53.2	3.2
	04-52-49	1.6
	05-42-13.3	3.2
	06-14-23.5	2.7
	06-19-41	1.6
	06-22-57	1.9
	07-52-17	2.1
	07-53-59.6	3.0
	08-13-48.3	4.2
	08-48-07	1.6
	09-18-55	1.8
	10-34-54	1.6
	10-57.3	2.2
	10-59-45	1.6
	11-00.1	1.6
	11-02-06	2.0
	11-17-06	1.6
	11-52-08	2.8
	12-54-32.5	3.8
	13-02-17	1.8
	13-24-03	2.3
	13-33-59	1.9
	13-48-42	1.7
	13-56-11	2.0
	14-22-33	2.6
	14-59-03	1.8
	16-02-48	2.5
	16-40-51	2.4
	16-48-54	1.9
	16-56-31.9	2.8
	17-36-13.7	3.3
	17-48-17	1.7
	18-11-54	2.6
	18-26-42	2.2
	18-42-58	1.6
	19-43-36	1.7
	19-50-52	1.7
	20-11-53	2.5
	21-33-44	2.2
	22-12-09	2.0
	22-48-00.5	3.5
	22-49-16	2.6
	22-53-55	1.9
	22-55-16	2.3
	23-06-24	1.6
	23-23-18	1.8
Date 1957	Origin time (GCT) h m s	Magnitude
Mar. 24	00-35-27.6	3.1
	01-37-22	1.7
	02-00-07	2.3
	02-54-54	2.3
	03-35-59.5	3.2
	03-52-00.3	2.8
	04-46-12	2.0
	05-09-17	1.6
	05-30-14	2.5
	05-43-13	2.2
	06-26-50.6	2.7
	07-41-34	2.0
	09-02.5	1.6
	11-31.5	1.7
	14-59-05	1.7
	15-34-12	2.4
	17-43-13	1.6
	19-11-16.4	2.8
	19-52-33.1	2.5
Mar. 25	00-22-23.7	2.7
	02-39-12	2.0
	03-01-59	2.3
	04-27-31	1.7
	04-42-07	1.6
	05-04-48	2.0
	08-05-09.8	2.7
	09-31-11.2	2.6
	10-27-30	1.7
	12-36-09	2.0
	17-20-17	1.8
Mar. 26	05-13-57	1.7
	05-52-14	1.6
	07-13-32	1.8
	07-48-56	2.0
	09-14-30	2.2
	14-51-29.1	2.7
	14-51.8	2.6
	15-20-53.4	2.4
	20-58-19	2.4
	23-19-49	1.8
Mar. 27	00-51-41	2.0
	02-13-24.6	3.1
	07-04-49	2.3
	09-09-48	2.8
	10-41-52.8	3.1
	12-03-01	1.7
	13-05-18	1.7
	15-58.3	1.9
Mar. 28	06-14-19	2.0
	06-24-05	1.6
	07-46-44	2.2
Mar. 29	04-52-13	1.6
	07-05-49	1.6
	19-27-26	2.8
Mar. 30	07-48-33	2.9
	21-12-36	2.4
Mar. 31	00-03-51	2.0
	01-35-28	1.6
	16-43-26	2.4
Apr. 1	07-48-17	1.9
Apr. 2	11-46-10	1.9
	21-21-18	2.0
Apr. 3	19-47-26	2.2
Date 1957	Origin time (GCT) h m s	Magnitude
Apr. 4	17-32-34	1.8
	20-06-45	2.8
	23-39-08	2.8
Apr. 7	16-20-30.3	3.3
Apr. 8	00-18-24	2.9
Apr. 9	22-21-23	2.4
Apr. 10	11-08-43	2.1
	11-42-27	2.2
Apr. 11	06-25-10	2.8
Apr. 13	13-21-09	2.2
	20-23-35	2.9
Apr. 14	23-00-02	2.9
Apr. 15	15-24-55	1.8
	15-57-56	2.2
Apr. 16	15-30-46	2.1
Apr. 17	12-53-57	2.1
Apr. 19	03-53-44	1.8
Apr. 21	18-55-24	2.8
	21-38-09	2.9
Apr. 23	14-34-40	1.9
Apr. 27	00-15-04.0	3.0
Apr. 28	11-12-07	2.7
Apr. 30	06-27-46.1	3.4
May 1	19-36-22.5	3.3
	23-26-33	2.4
May 5	01-12-25	1.8
May 6	18-43-59	2.1
May 8	19-36-04	2.7
May 13	01-08-27	2.3
May 16	11-22-37	2.4
May 19	03-22-35	2.6
	15-03-14	2.5
June 3	18-14-47	2.7
June 12	07-39-00	2.0
	09-04-47	1.7
June 13	10-40-55.5	3.0
June 14	03-43-02	2.6
	10-22-55	2.1
June 15	18-51-18	1.8
June 27	04-38-02	2.9
	21-32-51	1.9
June 28	09-58-20	2.2
July 12	08-27-24	2.2
	08-28-00	2.0
July 23	04-28-54	2.2
Aug. 17	05-24-11	2.9
Aug. 19	16-36-23	2.3
Aug. 27	12-34-34	1.8
Sept. 11	04-59-20	2.0
Sept. 14	02-25-20	1.8
Oct. 28	02-38-12	2.4
Nov. 20	07-47-53	2.6
1958		
Jan. 16	00-58-56	1.8
Feb. 7	03-58-14	2.3
Feb. 18	21-34-24	1.8
Feb. 23	21-15-12	1.6
Mar. 6	21-42-52	2.3
Mar. 19	11-58-51	2.0
Mar. 28	14-05-39	2.5
May 2	13-10-47	2.1
May 4	07-52-44	2.6

or the volume of rock contributing strain energy to the shock. Wilson (1936) first suggested that the distribution of the smaller shocks accompanying a large earthquake might well indicate the focal region of the main shock.

Only in comparatively recent years has coverage by sensitive, short-period seismographs improved sufficiently that, in some areas, a reasonably precise distribu-

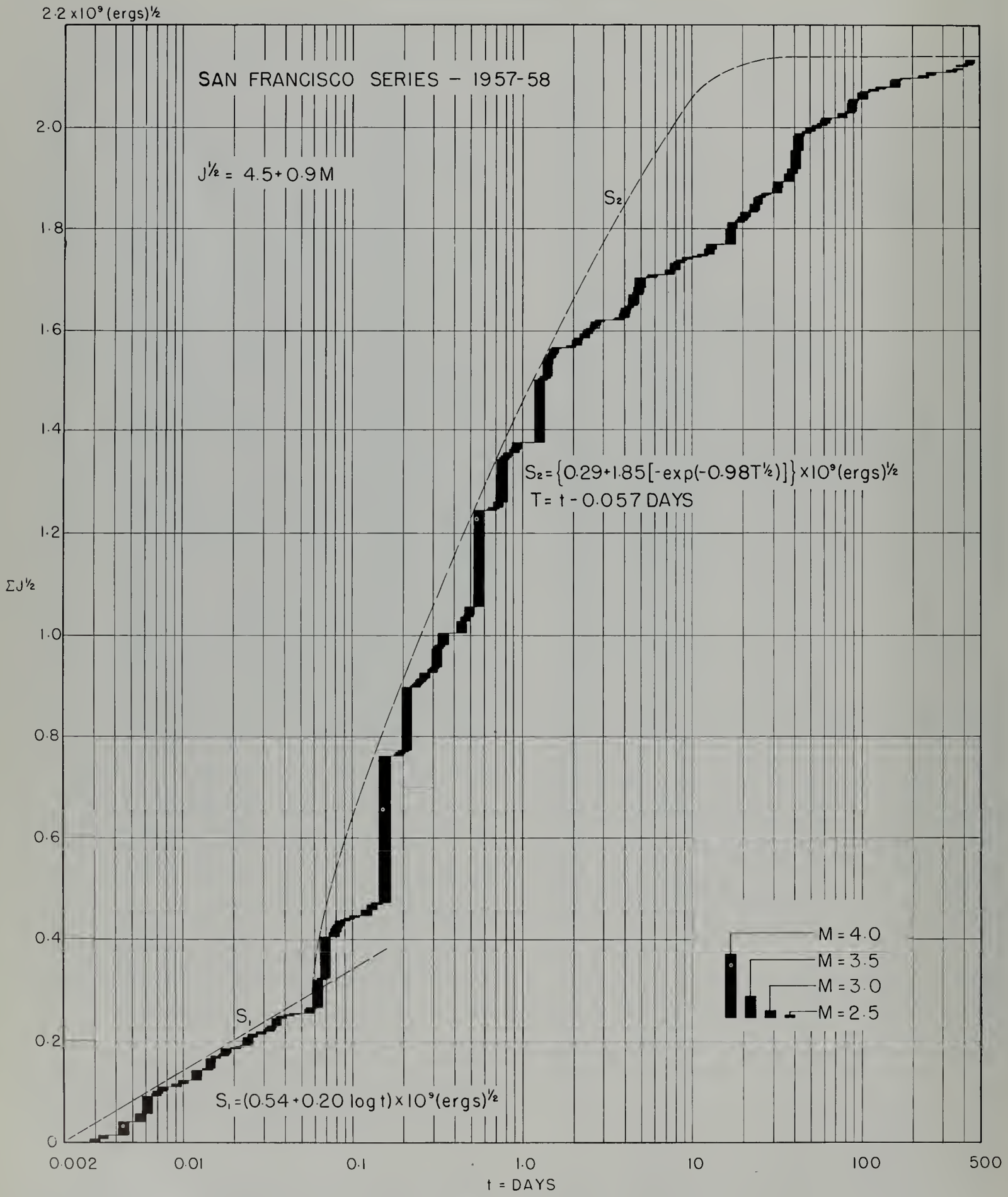

FIGURE 3. Elastic strain rebound characteristics of the aftershock series.

tion of aftershock epicenters in the neighborhood of a large earthquake can be determined. Wilson (1936) located epicenters for the five best-recorded aftershocks of the Nevada earthquake of December 20, 1932, and for 11 foreshocks and aftershocks of the Parkfield, California, earthquake of June 4, 1934. In the latter series, almost all useful seismograms were from stations either northwest or southeast of the main shock, which was in the San Andreas fault zone in southern Monterey County. Because of the limited azimuthal distribution of stations, he assumed all 11 shocks also to be along the fault zone, and reported epicenters in terms of distance northwest or southeast of the main shock. With additional stations and more sensitive instruments at many of the older stations, Richter (1955) found that the aftershocks of the Arvin-Tehachapi earthquake of July 21, 1952, were not confined to the immediate vicinity of the White Wolf fault zone which broke at the time of the principal shock, but were distributed over an area of 2100 km^2 or more. Aftershock epicenters covered about equal areas on the two sides of the breaks in the ground surface.

If Wilson's suggestion is valid, focal coordinate data from the foreshocks and aftershocks of the 1957 San Francisco earthquake then serve to delimit the focal region of this shock in all three dimensions. Its horizontal extent is indicated approximately by the hatching in figure 2; the bulk of the well-located epicenters are contained within a surface area of 25 km^2. Furthermore, the bulk of the foci lie in a range of depth of 7 km. The volume of the focal region or strain zone is thus about 175 km^3. The extent of the strain zone parallel to the San Andreas fault is effectively defined by the two largest aftershocks, nos. 14 and 22; the distance between them, 9 km, is an approximate measure of the length of the fault slippage of the main shock.

With a zone of such limited extent in all three dimensions, the uncertainty in focal coordinates assumes more importance than it would if the dimensions of the strain zone were large compared with the uncertainty. Thus, in figure 2, the entire surface area of the hatched zone lies within about 2 km of the San Andreas fault; 2 km is also the estimated uncertainty in a single epicenter location. It thus is possible that all the foci were close to a single fault plane, and that the apparent spread is due solely to the uncertainties in location. For this reason, the 25 km^2 estimate for the surface area of the strain zone must be regarded as a maximum value. Similarly, the spread of 7 km in the focal depths and the 9 km of tearing along the San Andreas fault in the main shock should also be regarded as maximum values; the area of main shock fault slippage may have been as small as 5 km long by 3 km or less high.

Figure 3 shows the elastic strain rebound characteristics of the aftershock series in the form developed by Benioff (1951). In such a plot, the elastic strain relieved in any individual shock is presumed to be proportional to $J^{1/2}$. J is shock energy in ergs derived from shock magnitude M through the relation $\log J = 9.0 + 1.8\ M$. Thus at any time after the main shock, the total strain relieved by the aftershocks is proportional to $S = \Sigma J^{1/2}$, the summation including all aftershocks up to the time in question.

The aftershock activity of the 1957 San Francisco earthquake is of the dual form such as that observed by Benioff (1951) in the 1933 Long Beach earthquakes. During the first 0.057 day (1.37 hours) following the main shock, the elastic strain rebound characteristic is well represented by the form $S_1 = a + b \log t$. According to Benioff's theory of aftershock generation, such a form is produced by elastic afterworking resulting from a compressional strain of the rock in the focal region. An abrupt change in the form of the characteristic commences about 82 minutes after the main shock. The curve labeled S_2 in figure 3 is drawn with the form $S_2 = A + B\ [1 - \exp(-CT^{1/2})]$, which, according to Benioff's theory, represents elastic afterworking of a shearing strain of the rock in the strain zone. The fit of the observations of the first 82 minutes to S_1 is reasonably good; the fit to S_2 thereafter is much less satisfying, although the change in form of the characteristic is quite evident. The separation of aftershocks into two groups, one on one side of the parent fault exhibiting the compressional strain characteristic, the second on the other side exhibiting the shear strain characteristic, as found by Benioff (1955) in the 1952 Kern County earthquakes, did not occur in the 1957 San Francisco series.

It is evident in this series, as in others reported by Benioff, that a relatively small number of large aftershocks contribute the major share of S. The observed data (see figure 3) appear as a series of large jumps in S (i.e., the larger aftershocks) separated by more gently rising segments representing a rather large number of small aftershocks. A similarity in the slopes of these gently rising segments is apparent over much of the series, regardless of over-all type (i.e., compressional or shear) of the curve. The existence of two different types of aftershock-generating mechanism is suggested by the onset at 82 minutes of an abrupt change of slope of the curve for S; however, separation of the aftershocks by type of generating mechanism would, in this particular series, appear to be more by shock magnitude rather than by geographic location (as in the Kern County series). No definite criterion for making such a separation is apparent in this series, however, so that there are no means available to clarify the shape of the curve represented by aftershocks generated by the delayed action mechanism.

For the main shock (M = 5.3), the elastic energy release J amounted to 3.2×10^{18} ergs (based on the relation $\log J = 9.0 + 1.8\ M$), and thus the average elastic strain energy density in the rocks before the earthquake was $j = J \div V = 3.2 \times 10^{18}$ ergs $\div 1.75 \times 10^{17}$ cm^3 = 18 ergs/cm^3. Following the procedure outlined by Benioff (1955, esp. pp. 200-201), additional stress and strain characteristics can be computed. The following are based on a value of the elastic constant $\mu = 5 \times 10^{11}$ and on the assumption that 100 percent of the elastic energy is converted to seismic wave energy [corresponding values given by Benioff for the Kern County earthquake of July 21, 1952 and its aftershock series appear in square brackets]:

Purely elastic strain before main earthquake
$\varepsilon = 0.85 \times 10^{-5}$ [5.2×10^{-5}]

Total strain release in main earthquake
$J^{1/2} = 1.8 \times 10^{9}$ ergs$^{1/2}$ [2.2×10^{11} ergs$^{1/2}$]

Total strain release in aftershocks
$\Sigma J^{1/2} = 2.1 \times 10^{9}$ ergs$^{1/2}$ [1.5×10^{11} ergs$^{1/2}$]

Total strain (elastic creep plus purely elastic) before main earthquake
ε total $= 1.8 \times 10^{-5}$ [8.7×10^{-5}]

Average elastic stress borne by the rocks just before fracture
$\sigma = 9$ kg/cm^2 [26 kg/cm^2]

Total relative slip of the two fault surfaces during the main shock (based on a width of strain zone of 4 km)
$y = 3.4$ cm [190 cm]

These values are at best very rough approximations, depending strongly on the constants in the magnitude-to-energy conversion formula and on the very uncertain volume of rock in the strain zone. As the strain zone volume used in deriving the above quantities probably is a maximum value, the values given for ε, ε total, σ, and average elastic strain energy density should be considered as minimum values insofar as they depend on V.

A magnitude-to-energy formula of the form $\log J = a + bM$, in which a and b are constants, has been used by Benioff throughout the development of his theory of aftershock generation. The particular values of a and b used in the preceding paragraphs of this paper were those used by Benioff (1955) in his study of the 1952 Kern County aftershock series, and were chosen above to give comparable values of the various stress and strain characteristics quantities for the 1957 San Francisco series. In a recent revision of the magnitude-to-energy conversion formula, Gutenberg and Richter (1956) have related "unified" magnitude m to shock energy through $\log J = 5.8 + 2.4$ m; they find that, approximately, $m = 0.63M + 2.5$, so that the appropriate values of a and b for use with a series of small aftershocks would be 11.8 and 1.5, respectively. Relative to $\log J = 9.0 + 1.8M$, these revised values of a and b yield higher energies over the entire observed range of magnitudes, with the relative difference greatest for the lower magnitudes.

The main shock energy and stress and strain characteristics given below were computed with no change in methods or assumptions except the substitution of $\log J = 11.8 + 1.5M$ for $\log J = 9.0 + 1.8M$:

$J = 5.6 \times 10^{19}$ ergs (main shock)
$j = 320$ ergs/cm^3
$\varepsilon = 3.6 \times 10^{-5}$ (pure elastic strain)
$J^{1/2} = 7.4 \times 10^{9}$ ergs$^{1/2}$ (main shock)
$\Sigma J^{1/2} = 17.4 \times 10^{9}$ ergs$^{1/2}$ (aftershocks)
ε total $= 1.2 \times 10^{-4}$
$\sigma = 60$ kg/cm^2
$y = 14$ cm.

Here energy, stress, and strain are all appreciably greater than the corresponding values obtained with the earlier magnitude-to-energy conversion formula; the elastic creep-strain release in the aftershocks is relatively greater than the purely elastic strain release in the main shock. The comparison again emphasizes the roughness of approximations of this sort; improvement of our insight into the conditions of stress and strain which lead to large earthquakes and their aftershock series must await more definitive methods of computation of shock energies.

FOCAL MECHANISM OF THE MAIN SHOCK

A method for determining the direction of faulting in an earthquake by a study of the distribution of the direction of the initial motion of the ground at seismographic stations has been developed by Byerly (1955, which summarizes his method and extensions by others). Work by a number of authors using Byerly's method clearly demonstrates that its proper application can yield results which are geologically plausible, even in the absence of observed fault displacements at the earth's surface.

In general, the method defines two planes at the focus. Byerly bases his interpretation of these planes on Nakano (1923), who investigated the accelerations which would be set up in an isotropic, homogeneous earth disturbed by a force couple acting along a fixed direction in the earth. One plane contains the active fault surface, the other is normal to the direction of action of the force couple, and thus defines the direction of motion of the sides of the fault. The pattern of first motion directions by itself cannot distinguish between the two planes. This decision, if it can be made at all, must be based on other considerations.

The first-motion data used to plot the fault-plane solution (figure 4) are given in table 3. No entry in the last column indicates that the direction of motion was not determined, either because of a very weak beginning, or because of uncertainty as to the relation between the directions of seismogram and ground motion. Parentheses around a direction of motion indicate moderate doubt owing to a weak beginning. The beginnings of P at stations more distant than Rapid City ($\Delta = 15.9°$) were too weak to be useful.

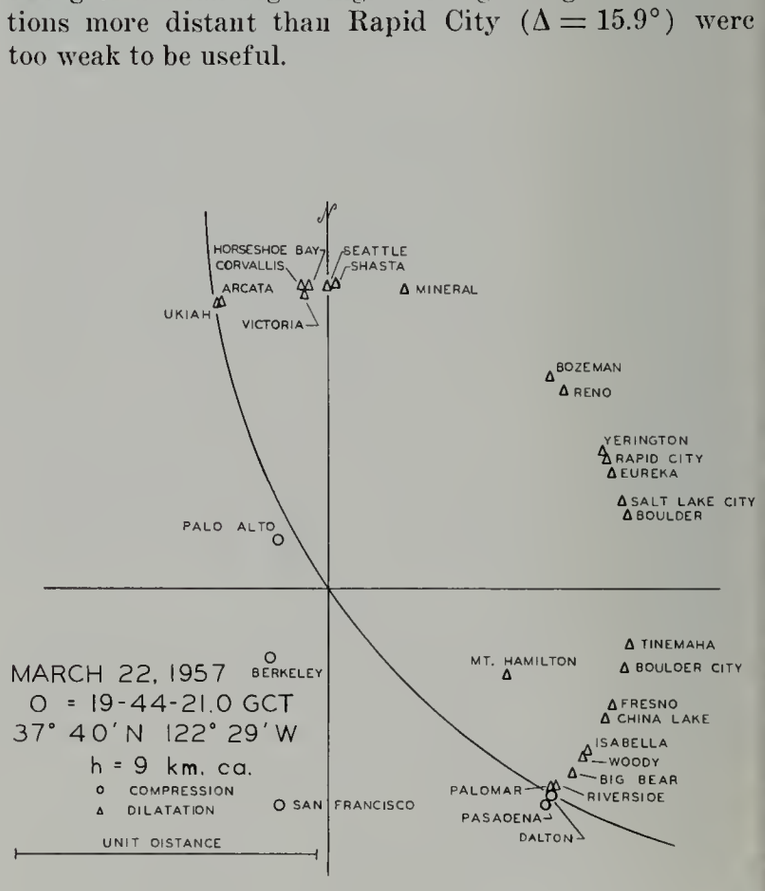

FIGURE 4. Fault-plane solution.

The focus is at the origin of figure 4, with each station except Berkeley, Palo Alto, and San Francisco plotted at its proper azimuth and at a distance from the focus proportional to the tangent of the angle of emergence at the focus of the seismic ray to each station. The ray paths to Berkeley, Palo Alto, and San Francisco depart from the focus above the horizontal; in accord with the procedure described by Hodgson (1953, pp. 50-51) these stations are plotted azimuths opposite to their true bearings from the focus. The crustal structure used in the earlier section on *P Travel-Times for the Main Shock* to compute travel-times was also used to determine the angle of emergence at the focus. This method of computing extended distances of stations on straight-line portions of the P travel-time curve was first used in studies of the 1954 central Nevada earthquakes (Tocher, 1955; Romney, 1955, 1957). It eliminates the difficulties associated with the Hodgson and Storey (1953) tables of extended distances for crustal foci, which are based on travel-time tables in which the apparent surface velocity increases continuously with distance, even in the P_n range of distances. It also permits one to plot stations at any epicentral distance on a single stereographic projection. Such a projection has the convenient property of projecting circles on the "extended" earth into circles on the map, and thus seems preferable to near-station maps of the type published by Ichikawa (1957, figs. 4 and 6) and by Sutton and Berg (1958, figs. 2 and 3).

The range in possible dips and strikes of one circle only are given by the distribution of first motions in figure 4. The maximum dip, 89.7° to the northeast, is determined by the compressions at Palo Alto and Dalton, which must lie southwest of the circle. This circle of maximum dip strikes N. 46° W. The minimum allowable dip, 77.6° NE, is determined by the dilatations at Ukiah and Dalton, which must lie inside the circle. Strike of the minimum-dip circle is N. 35° W. The San Andreas fault dips steeply, and in the vicinity of the epicenter strikes about N. 35°-38° W. Identification of the one circle defined by first motion data with the San Andreas fault is therefore a natural step, although not uniquely required by the data.*

The alternate interpretation that the circle defined in figure 4 represents the auxiliary plane (i.e., the plane normal to the movement vector), while not excluded by the seismic data, seems rather implausible on geologic grounds. The fault-plane would not be uniquely defined, but would be limited to a plane of very low dip, with the down dip direction toward the ocean between N. 35° W. and S. 45° E. The movement vector, defined by the circle in figure 4, would then indicate that the hanging wall (ocean side) of the fault overrode the footwall (continental side).

If the circle in figure 4 is indeed the fault plane circle, certain additional conclusions can be drawn regarding the mechanism of this earthquake. The auxiliary circle, while not delimited by the available data, must be very small. The loci of possible centers are limited by Adkins' Orthogonality Criterion (Adkins, 1940; De Bremaecker, 1956), and the circle must pass through the origin and must be drawn to exclude all plotted stations. If the strike-slip component of movement on the San Andreas fault is right-lateral, the largest possible circle (limited by Berkeley and Mount Hamilton) has a dip of about 35°. The largest possible auxiliary circle which would give a left-lateral sense to the strike-slip component of movement has an even smaller dip, as this circle would have to be drawn so as to exclude Palo Alto and Berkeley.

While the dip and strike of the defined circle agree reasonably well with the dip and strike of the San Andreas fault as given by geologists, the nature of the movement was not a repetition of the observed right-lateral movement of 1906. Instead, the fault-plane solution would suggest movement on a steeply dipping thrust fault, with the continental side rising with respect to the oceanic side. The strike-slip component of the movement, if any, was at most only about half the dip-slip component.

* An earlier version of figure 4, in which the direction of motion at one station—China Lake—disagreed with the adopted fault-plane solution, was shown as a lantern slide at the Eugene Meeting of the Seismological Society of America, March 29, 1958. I am indebted to Professor Charles F. Richter for the information that this apparent disagreement had resulted from an inadvertent reversal of galvanometer connections which was overlooked when the China Lake seismograms were first loaned for this study.

DAMAGE TO BUILDINGS AND OTHER STRUCTURES DURING THE EARTHQUAKE OF MARCH 22, 1957

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Structural Engineers, Pacific Fire Rating Bureau

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ABSTRACT

Interesting damage was done to buildings and other man-made structures during the earthquake of March 22, 1957. As the earthquake was not of high intensity or long duration, damage to dwellings was limited, in most cases, to plaster cracking. The concentration of damage to dwellings in one section of Daly City is probably related to local soil and geologic factors rather than to building construction.

Multistory buildings closest to the field epicenter were of earthquake-resistant construction and had no structural damage. The non-structural damage that did occur was of minor extent. In downtown San Francisco there were several instances of damage to older multistory buildings, and most of this damage was confined to plaster and partition cracking. In some instances, pounding between adjoining buildings was the principal cause of damage.

Most damage to low buildings can be laid to local ground conditions, design practice, or construction details.

Overall loss to buildings and other structures, excluding their contents, has been estimated at about $1,000,000.

INTRODUCTION

The headlines in the daily press at the time of the San Francisco earthquake of March 22, 1957, implied that a major earthquake, causing considerable damage, had taken place. Actually, it was neither particularly intense nor damaging. Eight earthquakes occurred in California and Nevada within the 3 previous years, which were as strong or stronger than this one (see table 1).

Table 1. Recent California and Nevada earthquakes.

Earthquake location	Date of occurrence	Maximum Modified Mercalli intensity	Richter magnitude
Watsonville, California	April 25, 1954	VIII	5.3
Fallon, Nevada	July 6, 1954	VIII-IX	6.8
Fallon, Nevada	August 23, 1954	VIII-IX	6.8
Dixie-Fairview, Nevada:			
1st shock	December 16, 1954	VIII-X	7.1
2nd shock	December 16, 1954	VIII-X	6.8
Eureka, California	December 21, 1954	VII	6.5
San Jose, California	September 4, 1955	VII	5.8
Walnut Creek, California	October 23, 1955	VII	5.4
Imperial Valley and Baja California	February 9, 1956	Maximum not established	6.8
San Francisco, California	March 22, 1957	VII	5.3

Damage from the March 1957 earthquake consisted largely of plaster cracking and other non-structural damage to wood frame dwellings, plus loss of contents of these dwellings. Probably the damage to all other construction, such as multistory buildings, mercantile buildings, public schools, etc., was less than to dwellings.

The dollar evaluation of damage to dwellings in areas in which the earthquake had a Modified Mercalli intensity of VI or VII is difficult.* Damage at these intensities is largely plaster cracking. Where no brick chimneys exist, plaster cracking may be the full extent of the damage to dwellings. Too, home owners are likely to mistake pre-earthquake plaster cracks for earthquake damage. The authors have examined numerous dwellings said to have been "seriously" cracked, in this as well as other earthquakes, only to find paint in the cracks. This would indicate that the damage existed prior to the shock.

Based on loss adjustment figures from several insurance sources, data from the U. S. Coast and Geodetic Survey, and personal observations, we estimate the total actual damage to buildings and structures of all types to be about $1,000,000, plus an unknown amount of building contents loss. Building damage, including damage to dwellings, was usually considerably less than 5 percent of the building value, and only in isolated instances did the loss for dwellings exceed 5 percent.

Highest earthquake intensities occurred in areas having new construction, and this construction was largely earthquake-resistant. The earthquake intensity was too light generally to cause damage in regions with considerable nonearthquake-resistant construction, such as buildings with nonreinforced brick bearing walls constructed with sand-lime mortar.

* An isoseismal map is included with the paper by William K. Cloud in this volume, which shows areas of intensities VI and VII.

Reference will be made to the epicenter of the earthquake throughout this paper. The instrumental epicenter, discussed by Don Tocher elsewhere in this volume, is on, or near, the San Andreas fault in the vicinity of Mussel Rock on the coastline about 3 miles south of the San Francisco-Daly City boundary line.

The observed damage pattern would indicate a somewhat similar location for the field epicenter. The strongest earthquake effects were along the ocean front of Daly City and in San Francisco's Lake Merced area. The isoseismal map in the paper by William K. Cloud should be referred to for further details. The field epicenter is determined by the damage pattern. Instrumental and field epicenters do not necessarily coincide. For example, in the San Jose earthquake listed in table 1, the instrumental epicenter was 8 miles east of the field epicenter.

Acknowledgments. This study was originally conducted by the Pacific Fire Rating Bureau for its earthquake insurance rating studies. In the public interest, Mr. A. W. Gilbert, General Manager, has released for publication information contained in the files of the Pacific Fire Rating Bureau.

Papers of this type require the collaborative efforts of numerous observers. The following persons or organizations have contributed time and effort in assisting the authors: Fire Chief J. E. Kennedy (Daly City), Otis T. Calhoun (Director of Public Works, Daly City), George W. Hopman (Building Department, Daly City), Admiral A. G. Cook (San Francisco Disaster Council and Corps), G. D. Burr (San Francisco Water Department), Gould and Degenkolb (Consulting Engineers), George Washington (Consulting Engineer), Theodore Tronoff Jr. (Consulting Engineer), Hayes and Little (Consulting Engineers), H. J. Brunnier (Consulting Engineer), Graham and Hayes (Consulting Engineers), Woodward-Clyde and Associates (Consulting Engineers), United Air Lines, Pan American World Airways, Pittsburgh-Des Moines Steel Company, P. E. Beckman and G. A. Peers (Pacific Gas and Electric Company), J. R. Rossum (California Water Service), R. C. Moseley (Pacific Telephone and Telegraph Company), Walter Wells (National Board of Fire Underwriters), L. M. McKinley (General Adjustment Bureau), Factory Insurance Association, Marsh & McLennan-Cosgrove and Company, Lew Wulff (California Division of Highways), and the Golden Gate Bridge and Highway District.

BUILDINGS

Single-Family Dwellings

Single-family dwellings in large sections of San Francisco and Daly City have certain characteristics not common throughout the metropolitan San Francisco Bay region. Many of these wood frame structures are located on 25-foot—or somewhat wider—lots, and often no space exists between the sides of adjoining dwellings. Also, these homes are conventionally two-story. The garage, laundry areas, storage areas, etc., are in the first story; the second story is living space. An arrangement of this type leads to numerous partitions in the second story with a minimum number of partitions in the first story. The front wall in the first story has numerous openings. The rear wall of the first story has fewer openings than

Photo 1. Daly City in foreground, with San Francisco's financial center at top center. Looking northeast. Pacific Ocean at lower left. Westlake Palisades housing tract is between bluff and highway in the foreground. Lake Merced district of San Francisco in left center. Parkmerced and Stonestown multistory apartment building in center and left of center. Photograph taken 9 months prior to the earthquake. *Photo by Moulin Studio.*

the front. Many of the side walls have no openings. The result is a building which in general is weak in the first story, especially against transverse lateral forces.

This basic house design is characteristic of a great many homes in San Francisco and Daly City and has been used by many builders. The degree of lateral force stability will vary somewhat with the design used by the individual builder, but the transverse lateral force resistance of the first story is theoretically the weakest region in practically all cases.

Daly City, which is primarily a residential community, has a population of more than 30,000. The western part has been built since World War II and is largely the work of one builder. Structural characteristics of these new homes are rather uniform, and are of the type discussed in previous paragraphs.

The following information on foundation materials has been furnished by Woodward-Clyde and Associates:

"In general the foundation materials in western San Francisco and Daly City are either aeolian or marine in origin. The natural foundation materials in the Westlake Palisades are composed primarily of intercalated layers of sands, silts, and clays. The materials are uniform over much of the area except in areas affected by localized erosion and subsequent deposition, where the materials are of a heterogeneous nature. Very fine sand appears to be the predominant material with silts and clays present in variable proportions.

"In western Daly City the average dry density of the natural material as determined by undisturbed samples of soil taken from test borings and test pits is approximately 116 pounds per cubic foot. Although the moisture content is dependent upon local physicial exposures, the average percent moisture of the soil under natural conditions is approximately 16.

"In the construction of engineered controlled fills in western Daly City, the mixing of the natural sands, silts, and clays into a more balanced type of material generally increased the density by several pounds per cubic foot. Tests show that materials used in the fill when compacted to maximum density in the laboratory, frequently exceeded the density of the natural in-place material."

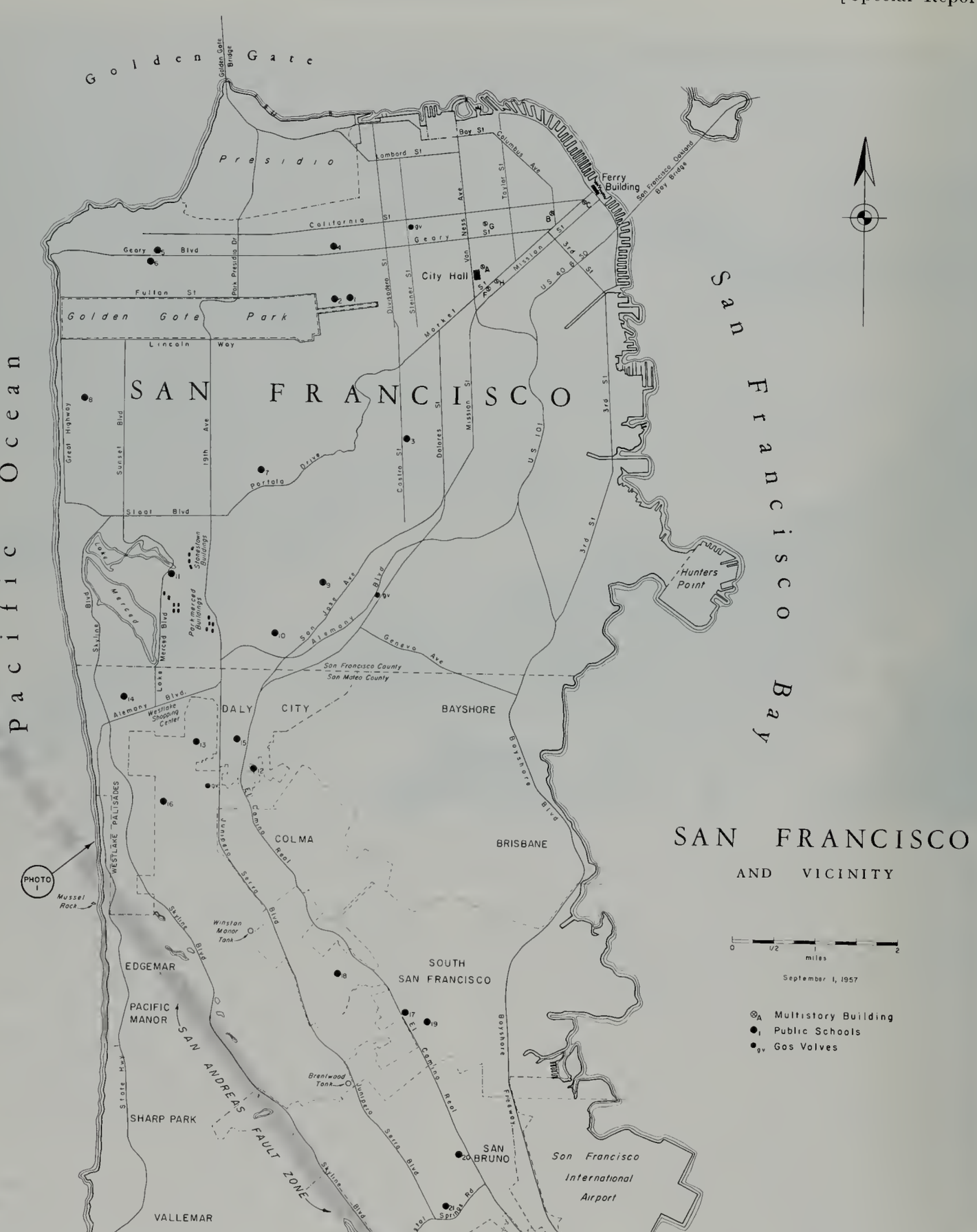


FIGURE 1. Map of San Francisco and vicinity showing locations of structures mentioned in text.

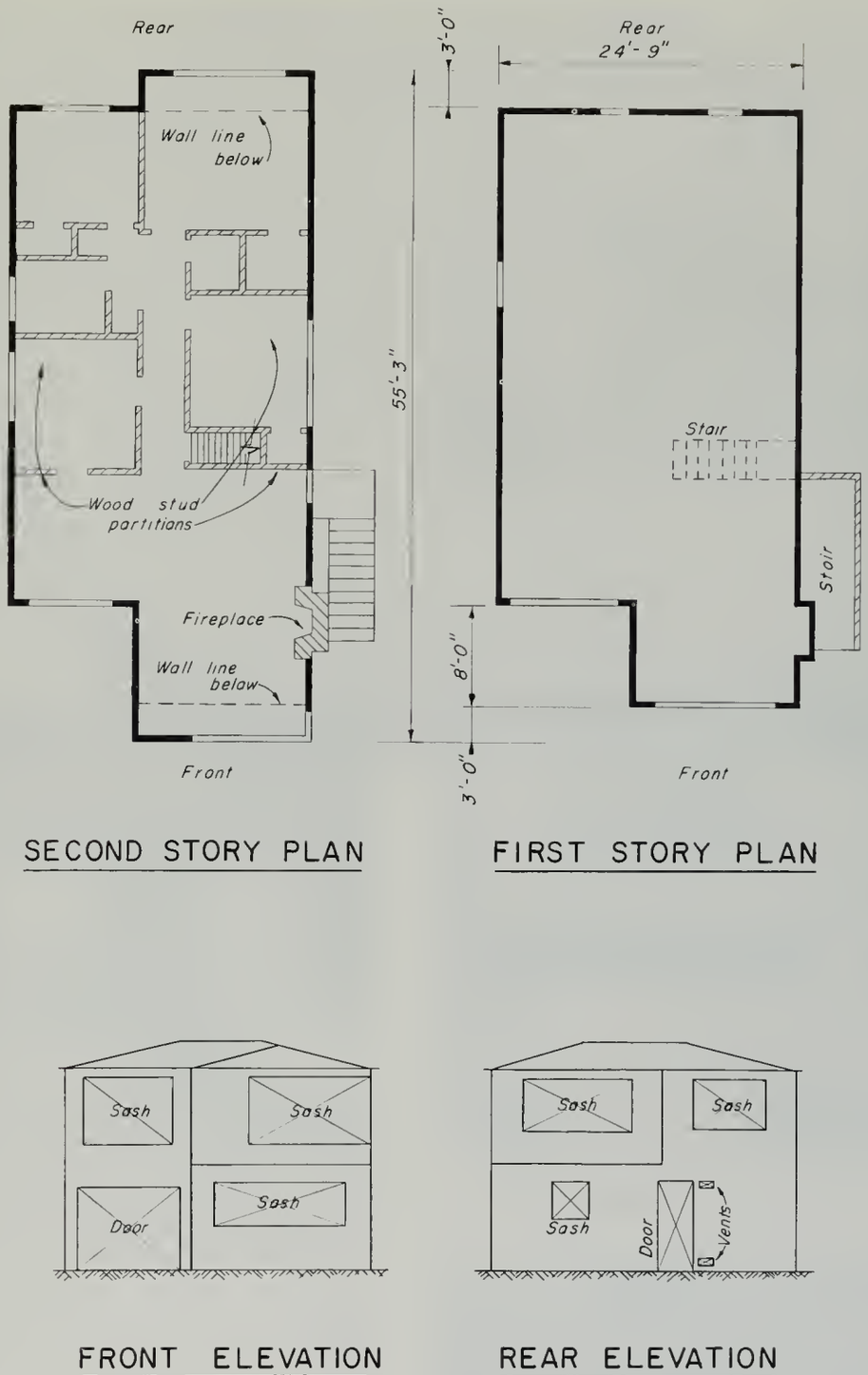


FIGURE 2. Diagrammatic plans of a typical two-story wood frame dwelling in the Westlake Palisades tract.

The fact that dwelling damage was concentrated in the Westlake Palisades district of Daly City and greatly reduced in adjoining housing tracts, is of considerable interest. The location of this tract may be seen in the vicinity map (fig. 1) and also in the aerial photograph (photo 1). The instrumental epicenter of the earthquake has been determined to be about 1 mile south of the Westlake Palisades tract.

Figure 2 is a diagrammatic plan and elevation of the construction of one particular home model in this tract. Numerous variants exist—that is, opposite hand layouts, different architectural trim arrangements, varying roof and roofing arrangements, fenestration, breaks in front wall, etc., but the lateral force resistance characteristics are largely the same.

All wall construction had 2 x 4 and 2 x 6 studs at 16-inch centers. Sidewalls were sheathed with gypsum board. Front and rear walls were usually diagonally sheathed with 1-inch wood boards, except that straight sheathing existed above and below openings in some instances. Therefore, the front elevation shown in photo 2 had little diagonal sheathing. As is the custom for dwellings, no special framing details were used at points of high lateral force stress concentrations in the front

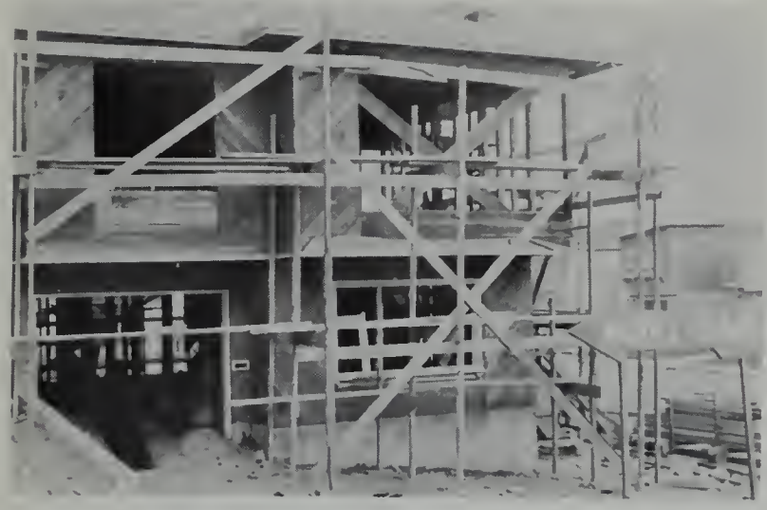


PHOTO 2. Front elevation of a Westlake Palisades home in course of construction. Diagonal sheathing on sides of front wall openings, straight sheathing above and below openings.

PHOTO 3. Typical cracking in first story at re-entrant corners of windows and doors. Westlake Palisades tract.

PHOTO 4. Another view of typical first story plaster cracking in Westlake Palisades.

wall. Foundations were nonreinforced concrete extending 8 inches below grade, according to the plans. The stud walls rested on redwood sills, which in turn were bolted to the concrete foundations with $\frac{1}{2}$-inch bolts at 6-foot centers. Some alternate construction details were noted in some houses.

A pair of 1 x 6 knecbraces was apparently installed at random on some side wall studs in the first story. The pattern varied from house to house; seven sets on a side was the observed maximum, and none the minimum.

The construction of all of these houses had been accepted by the local building department and by the Federal Housing Authority.

The earthquake damage to the structure of the houses was generally confined to the exterior plaster of the front wall of the first story. Usually there was no interior finish in the first story. The damage occurred at the theoretically weak locations previously discussed. The sheathing behind the plaster split in some instances. Some foundations broke, and at least one concrete ground slab had a major break (photo 5). However, the dollar loss to each home, excluding contents, generally did not exceed $200.

PHOTO 5. Broken concrete first floor slab. Slab rests on grade and is not reinforced. Damage due to local settlement. Westlake Palisades. *Photo by Mary Hill, courtesy California Division of Mines.*

The builder has been reinforcing the footings of dwellings erected since the earthquake. Also, diagonal sheathing is being placed above and below the openings in the first story in all cases.

The fact that the dwelling damage was so concentrated in the Westlake Palisades tract does not appear to be explainable by the construction, since the construction was the same on both sides of Skyline Boulevard. Soil conditions were also uniform. At the time of the shock, the Westlake Palisades tract contained over 550 wood frame dwellings, about 90 percent of which were two stories high and followed the plan shown in figure 2. Almost all had some damage, with perhaps 50 percent having pronounced plaster cracking in the front wall of the first story.

Photo 6. Fireplace damage, Westlake Palisades. *Photo by Art Frisch.*

Interiors of many of the homes were damaged. Some fireplaces collapsed. Plumbing damage is discussed later in this section.

The degree of damage within the Westlake Palisades tract varied markedly. Dwellings on one side of the street might have greater damage than those across the street. Attempts to correlate house orientation and minor construction variations were not conclusive.

The series of small noncontinuous ground cracks within the tract are not considered to be evidence of faulting, but may be explained by local conditions. If the cracks were evidence of fault movement, then damage effects should be the same on each side of the fault for similar construction on similar soils. This, of course, was not the case.

Cuts and fills exist throughout the Westlake Palisades tract, and some of the fills exceed 35 feet. All grading work was under the supervision of a qualified soils engineering firm. As indicated in previous paragraphs, better than 100 percent recompaction was indicated from their test samples. There was no soils engineering supervision for the minor cuts and fills made during the actual house construction. The engineering firm of Theodore V. Tronoff Jr., evaluated the damage to each dwelling on an arbitrary scale having 10 divisions, and the weighted results of 568 dwelling investigations showed that houses on the engineered fills fared as well or better than houses on cuts (or on original ground). Further, considerably greater cuts and fills of similar soils exist to the east of Skyline Boulevard and such occasional damage as was found was not related to the soils. We may conclude that the recompacted soil was not a significant factor in the damage.*

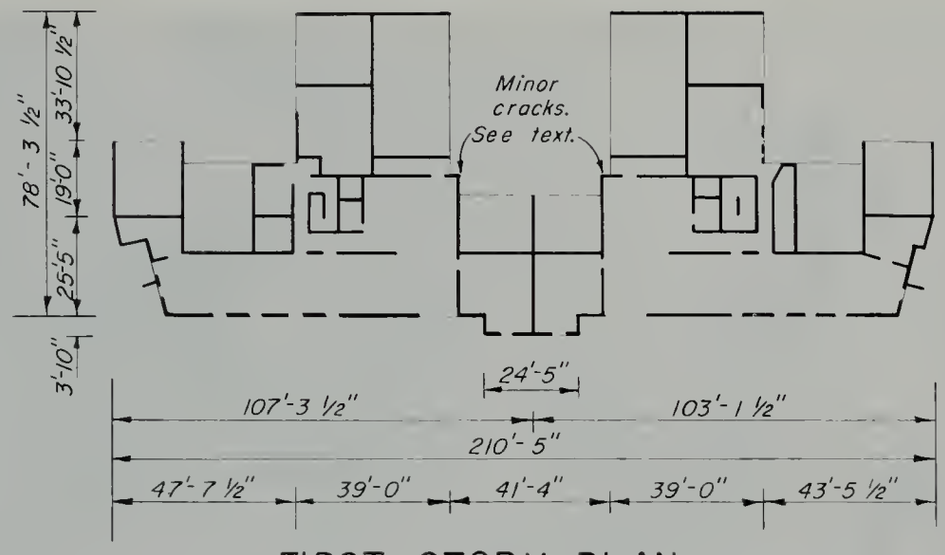
* Further information on soils and foundation materials may be obtained from the paper by M. G. Bonilla in this volume.

Retaining-wall damage and house settlement in some instances can be attributed to cuts and fills made during house construction and, therefore, are not necessarily an indication of the quality of the general grading work completed prior to construction.

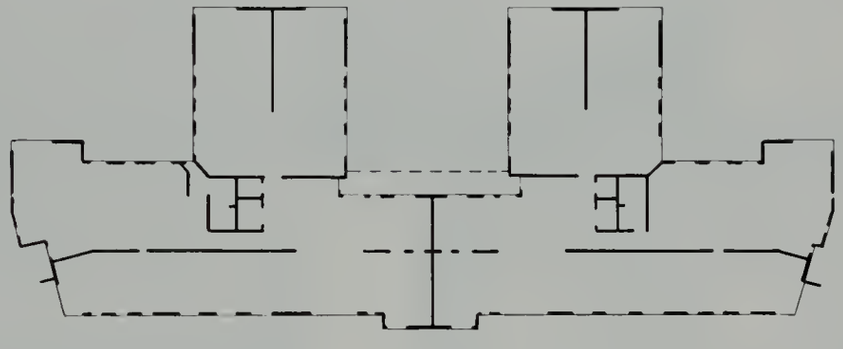
There is one suggested explanation that appears to fit the observed facts: The entire tract is on a bluff, the highest point being some 550 feet above sea level; if the area tended to lurch towards the ocean, then it would be reasonable to expect intensified ground motion and damage in a localized area.

Westridge Avenue in the Westlake Palisades tract is 600 feet long and is on a 12 percent grade. Cuts and fills along the street probably did not exceed 10 feet. Compression effects from ground shortening were noted on the sidewalks and curbs—the sidewalk buckled or heaved, expansion-joint material was compressed from the sidewalk joints, and there were compression failures in the concrete. This street is roughly oriented northeast-southwest and probably is in the direction of lurch movement. The next street to the south showed similar effects. Underground water lines parallel to these streets failed, from compression resulting from ground shortening. The entire area may also have slumped somewhat, and some survey data tend to confirm this. At the west end of Westridge Avenue, tension cracks were noted in the ground, particularly at one dwelling. These cracks ran at right angles to Westridge Avenue and parallel to the bluff; they appeared to be in a zone 20 yards wide by perhaps 100 yards long.

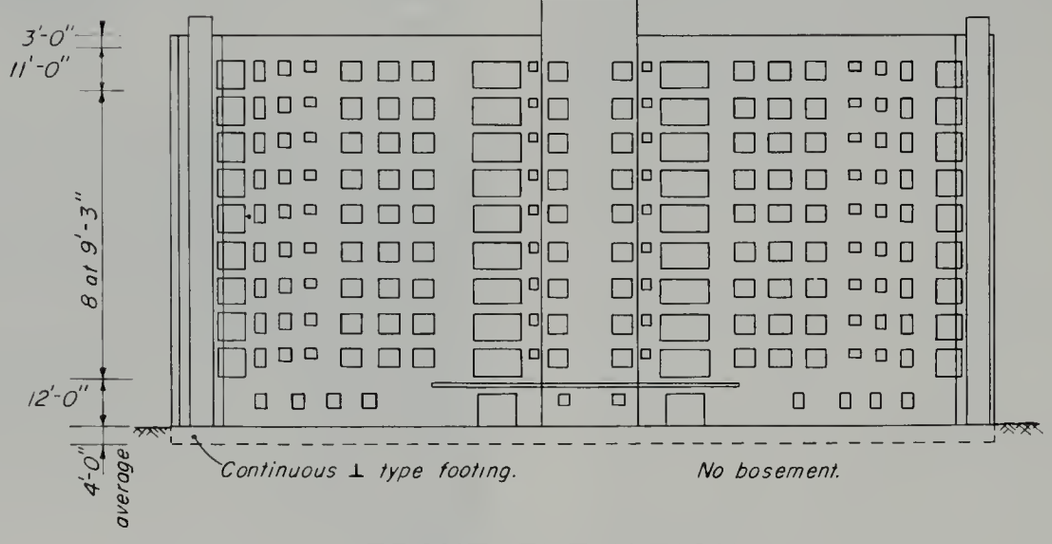
In an area of ground settlement elsewhere in this tract, borings placed since the earthquake have revealed what may have been a garbage dump, covered by sand long before the housing development was started. This



FIRST STORY PLAN



UPPER FLOOR PLAN



FRONT ELEVATION

FIGURE 3. Diagrammatic structural plan and elevation of typical Stonestown apartment building. Majority of exterior and main interior walls are 9 inches thick below the fourth floor and 8 inches thick above. Some small 6-inch walls at stairwells, elevator shafts, etc. Walls are bearing, and also act as shear walls for lateral forces.

points out the need for numerous borings, in order to catch local problems. Also, this indicates that a detailed history of an area may be helpful in disclosing local conditions that may not be revealed by borings.

Some ground cracks near the edge of the bluff could be associated with potential slides. The highway at the base of the bluff was closed after the earthquake because of slides, and slides have been a common problem in the past.

Plaster cracking was common in dwellings throughout the San Francisco Bay area, and it naturally diminished with distance from the field epicenter. The authors looked at numerous examples of plaster damage, with only too often the home owner honestly ascribing old cracks as fresh damage resulting from the March 1957 earthquake.

The Associated Plumbing Contractors of San Francisco reported that they received a total of 2,395 emergency calls in the first 52 hours following the earthquake:

Number of water heaters damaged	856
replacement required	125
Number of toilets clogged	291
replacement required	62
Wash basins damaged or fractured	175
Broken toilet tank covers	245
Broken sewer lines	97
Fractured, broken or bent gas supply lines	422
Total loss, home and office	$43,485

The bulk of these calls were from home areas; nearly 1,500 were in the residential areas south of Sloat Boulevard in San Francisco and north of Colma.

The water heaters which were damaged had nearly all toppled, after the copper supply line to the heater broke at the soldered connection. The heaters which had to be replaced had ruptured or punctured tanks. Clogging of toilets was caused by contents of medicine cabinets and other loose articles falling into the bowls. Many toilet tank covers were thrown off. Breaks in sewer lines occurred in the joint near the house foundation; most of the sewer lines were run under the foundation. Practically all of the gas service line damage occurred where water heaters toppled or moved, but a few service lines to furnaces were slightly damaged.

Multistory Buildings

Multistory buildings near the epicentral region, and in downtown San Francisco and Oakland, were generally only slightly affected by the earthquake, or affected not at all. The damage which did occur was mostly superficial, and in all known cases was nonstructural.

Lake Merced Area — Parkmerced Buildings. The eleven 13-story Parkmereed apartment house buildings are of considerable interest as they are among the closest multistory buildings to the most heavily shaken area (see fig. 1 for location). The buildings are reinforced concrete construction throughout. The exterior walls and some of the interior walls are of the reinforced concrete bearing wall type, and these walls are designed to take horizontal forces as well as vertical loads (Gould, 1952). Damage was very minor, and was in the form of superficial plaster cracking. No structural damage whatever was noted. It appears that the orientation of the buildings had no bearing on the amount of damage, and

Photo 7. Probably the most heavily damaged wall in a completed dwelling in Westlake Palisades. No dwellings collapsed or were near collapse. *Photo by Caterpillar Tractor Company.*

Photo 8. Cracking at sill line and breaks in nonreinforced concrete foundation wall in house under construction at Westlake Palisades. House did not shift on its foundations.

Photo 9. Separation at sidewalk joint at north end of Westlake Palisades. Some sliding towards ocean. Karl V. Steinbrugge in picture.

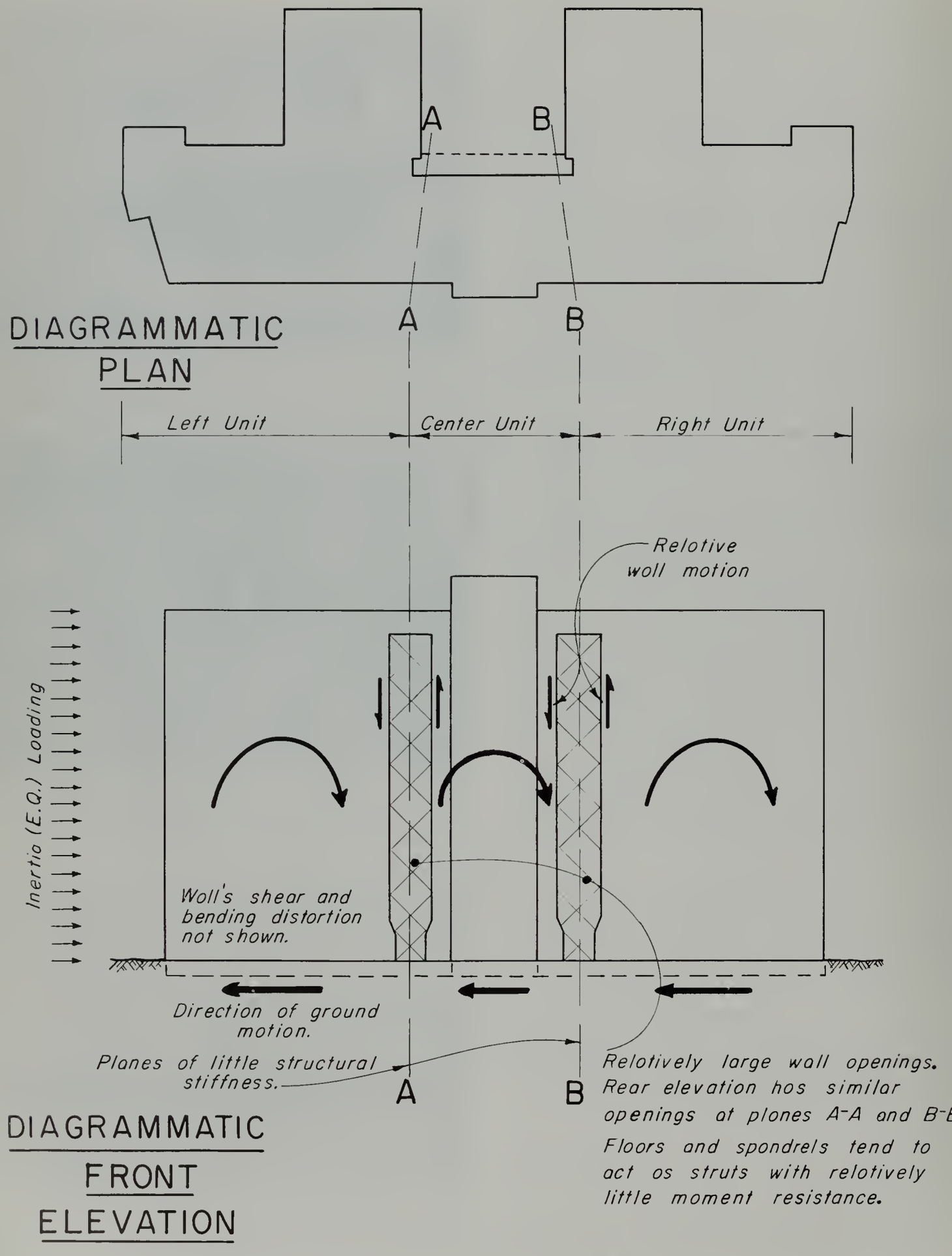


FIGURE 4. Presumed deflection resulting from lateral forces in a Stonestown apartment building.

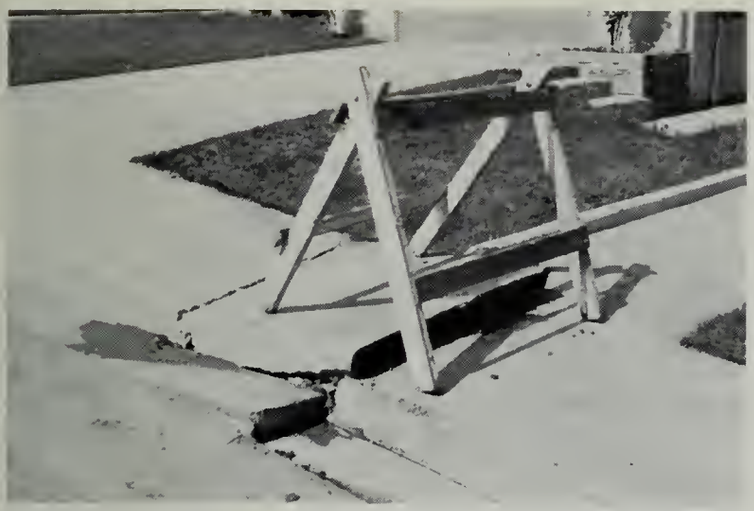


Photo 10. Ground shortening caused compression features such as these to several sidewalks in Westlake Palisades. Joint not at right angles to sidewalk surface, and this, along with asphaltic material in the joint, allowed heaving without concrete compression failures.

Photo 11. Front elevation of a Stonestown apartment building, San Francisco. Plywood panels in windows indicate broken glass.

there was no basic difference in the amount of damage between those buildings on piles and those on spread footings in the same area. The cracking that did occur happened at the joints between concrete and plastered walls. Cracking was a little more noticeable in the lower stories than the upper stories. There was somewhat similar superficial interior plaster cracking in the two story apartment units.

Lake Merced Area—Stonestown Buildings. The four 10-story Stonestown apartment house buildings, also close to the most heavily shaken area, had minor damage to some partitions. The damage to the windows formed an interesting pattern. A number of the front window panes, especially in the larger windows either side of the center offset (photo 12), were broken while fewer of the panes at the rear were broken.

It has been suggested that a reason for the difference in window-glass breakage between front and rear walls may be that all the glass was originally single strength, but that many of the rear planes had been replaced with double-strength glass prior to the earthquake.

Photo 12. Stonestown apartment building, San Francisco. Note that glass breakage is more extensive in the larger windows. *Photo by Wide World.*

The explanation for the nonuniform glass damage pattern may be relative motion between the structural elements. As indicated in figure 4, the building may be considered as three structural units from the lateral force standpoint. This is reasonable since the shear walls are not continuous at planes A-A and B-B, spandrel walls are smaller here than elsewhere, and no major floor beams exist to develop moments across A-A and B-B. It is suggested that each unit tended to rotate about its foundation (fig. 4). This effect, coupled with the shear and bending stresses in the concrete, may have resulted in relatively large vertical movements between the units mentioned. This explanation is somewhat substantiated by the slight crack in the concrete walls in the first story at the interior corners of the court formed by the two rear wings. However, the parapets, which are the only other major rigid structural elements between the units, had no cracking. There was no evidence of disturbed foundation material which could indicate excessive building rocking.

The orientation of the buildings somewhat affected the amount of glass damage, but the location of the damage within a building was consistent. Over-all partition damage was very minor and located primarily in the apartments having glass damage; this would support the theory of each building acting as three units. The buildings were designed to resist earthquake forces in accordance with the San Francisco Building Code.

San Francisco—Vicinity of the Civic Center. At least four buildings within a short distance of San Francisco Civic Center, approximately 5 miles from the

BUILDING F

PFRB file: 2726, 2726A

Built: 1938 & 1947

Occupancy: Stores & offices

No of stories: 9 & 11 plus basement

Foundation: Reinforced concrete spread footings on sand

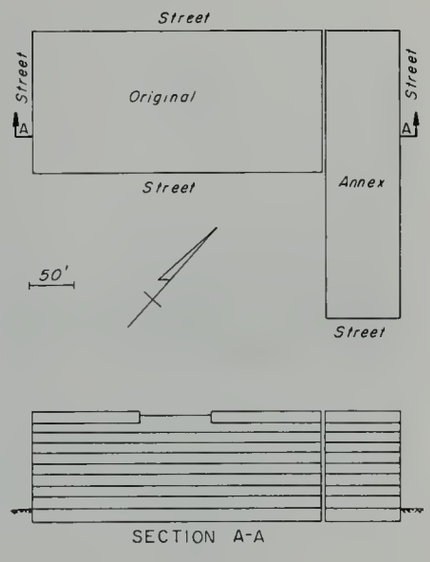
Frame: Reinforced concrete with some steel and wood frame in 9th to 11th stories

Wall const.: Reinforced concrete spandrels

Floor const.: Reinforced concrete, generally flat slab

Partitions: Numerous wood stud and gypsum board and glass

Adjoin. bldg.: None



EARTHQUAKE DAMAGE

MARCH 22, 1957, EARTHQUAKE

All Stories Plaster on ceilings and walls and asphalt tile on floors cracked at juncture between original building and annex. Cracks more pronounced in upper stories. Over-all damage is slight, and is about $12,000.

BUILDING A

PFRB file: 3284

Built: 1920 & 1931

Occupancy: Offices

No.of stories: 2 & 6 plus basement

Foundation: Reinforced concrete spread footings on sand

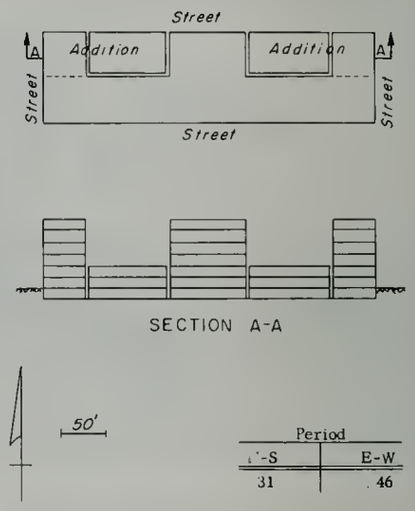
Frame: 6 story - steel frame; 2 story - reinforced concrete

Wall const.: Concrete brick panel

Floor const.: Reinforced concrete slab and beam

Partitions: Numerous hollow tile

Adjoin. bldg.: None



EARTHQUAKE DAMAGE

MARCH 22, 1957, EARTHQUAKE

5th to 2nd Separation cracks occurred in the main stairway between the plaster soffits and the metal stair stringers. More pronounced between 3rd and 4th floors. Horizontal cracks in north partition wall of the stairway approximately 6' above landing between 3rd and 4th floors.

1st Plaster cracks in walls where the two, two-story additions adjoin the original building.

BUILDING H

PFRB file: 707, 707A

Built: 1912-1924

Occupancy: Stores and hotel

No.of stories: 7 & 8 plus basement

Foundation: Reinforced concrete spread footings on sand

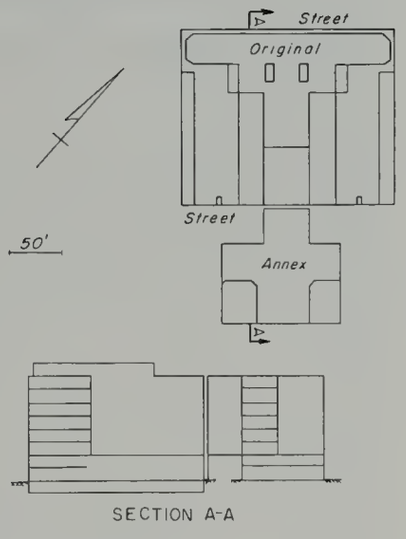
Frame: Reinforced concrete

Wall const.: Reinforced concrete panel

Floor const.: Reinforced concrete slab and beam

Partitions: Numerous hollow tile

Adjoin bldg.: E 1 story brick
W 2 story brick



EARTHQUAKE DAMAGE

OCTOBER 23, 1955, EARTHQUAKE

2 & mezz. Horizontal cracks in stairway behind north elevator at floor levels.

1st Vertical cracks in passage to kitchen.
All cracking occurred along previously repaired cracks. Cracking generally occurred in area at juncture of tower section to two story section.

MARCH 22, 1957, EARTHQUAKE

7th to 2nd Ceilings and walls cracked in all stories at juncture of annex to original.

2nd & mezz. Pattern of cracks similar to the cracking which occurred during October 23, 1955, Earthquake. Several partitions in mezzanine story were cracked at juncture to structural frame. Some windows cracked in 2nd story.

1st Several cracks in ceiling and partitions in and adjacent to lobby area.

BUILDING G

PFRB file: 51

Built: 1917 & 1951

Occupancy: Stores & offices

No.of stories: 6 plus 1 & 2 basements

Foundation: Reinforced concrete spread footings on sand

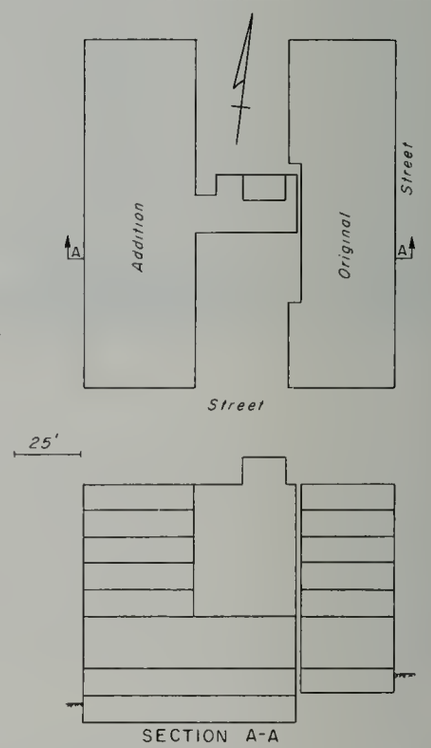
Frame: Reinforced concrete - original Steel & partial reinforced concrete - addition

Wall const.: Reinforced concrete panel

Floor const.: Reinforced concrete slab and beam

Partitions : Numerous metal stud and plaster

Adjoin.bldg : None



EARTHQUAKE DAMAGE

MARCH 22, 1957, EARTHQUAKE

5th Plaster cracked on both sides of hallway at juncture of the two sections.

5, 4, & 3 Plaster cracked on north side of hallway at juncture of two sections More pronounced in 5th story

2 & 1 No cracking noted.

FIGURE 5. Typical damage to multistory downtown San Francisco buildings. See figure 1 for their approximate locations.

BUILDING C

PFRB file: 1262

Built: 1917

Occupancy: Stores and offices

No.of stories: 1 & 11 plus basement

Foundation: Reinforced concrete footings on piles

Frame: Steel

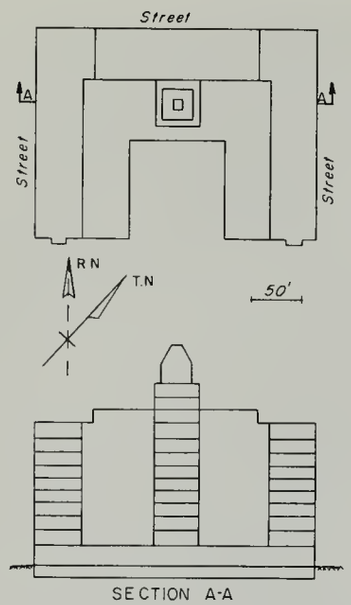
Wall const.: Brick panel & curtain

Floor const.: Reinforced concrete slab on steel beams

Partitions: Hollow tile, numerous in 1st, 2nd and 11th stories, and few in other stories

Adjoin. bldg.: None

PERIOD	
N-S	E-W
1.13	1.20



EARTHQUAKE DAMAGE

MARCH 22, 1957, EARTHQUAKE

Roof to 12th: No damage.

11th to 6th: Horizontal crack in stairway partition at 11th floor line. Separation cracks between plaster and metal stair stringer, with cracking becoming more pronounced in lower stories. Crack in west wall of 6th floor elevator lobby near corner at corridor.

5th: Two stairways exist below this floor. Separation cracks between plaster and metal stringer with cracking more pronounced at west stairway than at east stairway. East stairway continues to upper floors.

4th & 3rd: Cracks in stairway partitions with several sections of plaster having spalled from tile. Separation cracks along stringer, being more pronounced at top of stringers than at underside. Cracking in west stairway more pronounced than in east stairway. Cracks in these stories more pronounced than above.

2nd: Cracking at stairways similar to upper stories and to about same degree.

1st: Vertical crack in elevator shaft wall near corner in west stairway. There are numerous cracks in the partitions in the main (north) portion of the building and somewhat less numerous cracks in the partitions in the wings The most serious cracks in all sections of the building occur in partitions which are in line with the court walls above.

Basement: Walls at curb line have been settling with respect to the remainder of the structure and some additional settlement apparently took place during the earthquake and increased the size of the crack in the wall along the north side.

BUILDING B

PFRB file: 28

Built: 1920

Occupancy: Stores and offices

No.of stories: 15

Foundation: Concrete spread footings on sand

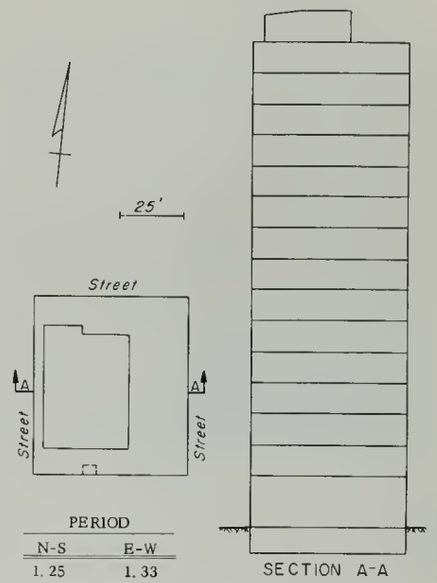
Frame: Steel

Wall const.: Brick panel.

Floor const.: Reinforced concrete slab and beam

Partitions: Numerous hollow tile

Adjoin.bldg.: S: 4 story concrete with wood roof.



PERIOD	
N-S	E-W
1.25	1.33

EARTHQUAKE DAMAGE

MARCH 22, 1957 EARTHQUAKE

Roof,pent,& 16: No observed damage.

15th: Slight cracks in corridor partitions where they abut structural columns and the elevator shaft walls. Separation crack between partition and vault.

14th: Slight movement of existing separation crack between partition and ceiling.

12th: No observed damage.

11th: Vertical crack in wall of restroom where tile partition abuts concrete shaft wall. Some cracking in partitions at northwest corner of building where they abut each other

10th to 5th: No observed damage except crack at juncture of corridor partition to column in 6th and 8th stories and a slight separation crack at the ceiling in the 6th story.

4th: Cracks at junctures of corridor partitions to columns at northeast and northwest corners of building.

3rd: Crack in restroom similar to that noted in 11th story Cracks in east wall of corridor at juncture with columns and where old openings have been sealed.

2nd: Cracking similar to 3rd. Most pronounced in this story.

1st: Several cracks where partitions adjoin columns.

FIGURE 6. Typical damage to multistory downtown San Francisco buildings. See figure 1 for their approximate locations.

previously mentioned multistory buildings, received pounding damage. Each of these buildings consists of two or more separate structural units abutting each other and having no structural interconnection. These buildings suffered damage to plaster, floor finishes, and exterior finishes when the sections of the buildings moved with respect to one another. The damage in each case was more pronounced in the upper stories than in the lower stories. One of these buildings was damaged in a similar manner during the Walnut Creek earthquake of October 23, 1955, but to a lesser degree.

San Francisco—Financial District. In the downtown financial district of San Francisco there was minor plaster damage to several of the many multistory buildings. Some construction details of certain buildings, in the financial district and elsewhere, and their damage patterns, may be seen in figures 5 and 6.

Building C, resting on piling and located in a poor foundation area, suffered more than average partition damage. The pattern of damage can be explained by the flexibility of the frame, especially in the high first story, and the configuration of the building. The extent of damage, compared to that suffered by structures on better foundation material, also suggests that the geologic conditions may have been a factor. The damage was most pronounced in those first-story partitions which were aligned with the court walls of the tower sections above. In the stairway partitions the damage was most pronounced between the third and fifth floors (photo 13).

A second building, located in the poor ground area, where there is only about half the thickness of under-

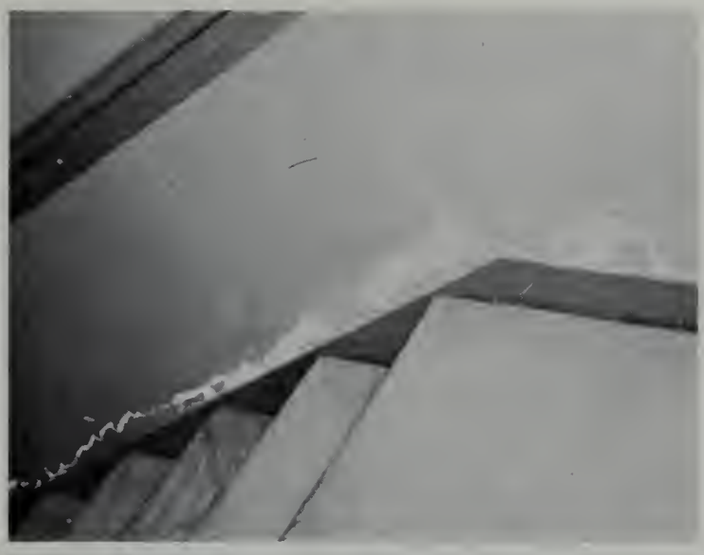


PHOTO 13. Typical damage around stairs in Building C, figure 6.

lying bay mud as at the site of Building C, suffered minor damage to partitions and ceilings throughout. The building deflected about half an inch with respect to the adjoining building at the roof line, damaging the flashing.

The Oakland City Hall, some 7 miles further from the epicenter than downtown San Francisco, had slight partition damage and one broken pane of glass. The partitions cracked along their junctures with the structural frame; the worst cracking was in the fourth and fifth stories of this 15-story steel-frame structure.

The Veterans Hospital in Oakland, formerly Hotel Oakland, which was damaged during the Walnut Creek earthquake of October 23, 1955, was not damaged during the March 1957 earthquake. This contrasts with the Oakland City Hall, which was not damaged in the 1955 earthquake.

One-, Two-, and Three-Story Buildings

Daly City. The J. C. Penney Department Store in the Westlake Shopping Center of Daly City is one story and mezzanine plus basement, with provisions for a second story. The structural steel frame and exterior walls for the future second story are already erected. The building is 150 feet 6 inches by 223 feet in plan. The floors and roof (future second floor) are 2½-inch reinforced concrete slabs on open web steel joists. The structure was built in 1955 and was designed to resist lateral forces. All vertical and lateral forces are taken by the steel frame. Structurally this building is classed as flexible, although the frame is heavier than normal (because of the future second floor). Welded continuity connections are used on all joints in the steel frame; first story columns are 14WF111 on an approximate 21-foot by 25-foot grid. The frame is fireproofed with vermiculite plaster, but this type of fireproofing is not effective in stiffening the frame.

The 5-inch-unit masonry veneer in the first story broke at three locations during the earthquake (photo 14). Although some question may exist regarding the type and extent of the anchorage of the masonry veneer to the steel studs, damage was clearly the result of the structural elements being more flexible than the rigid

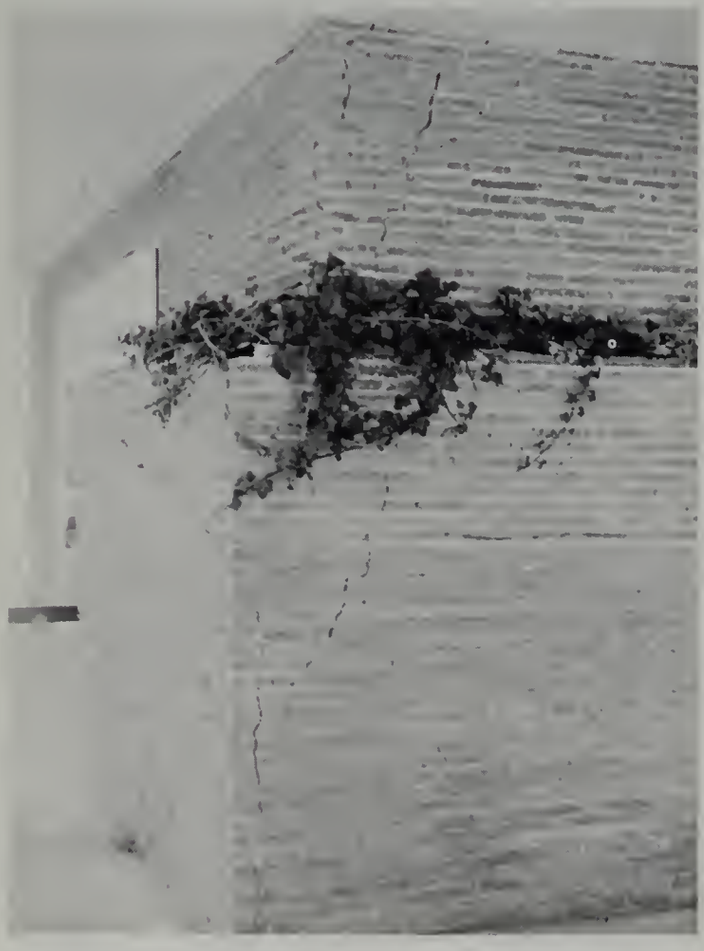


PHOTO 14. Veneer damage to Penney's Store, Westlake Shopping Center, Daly City. Damage to contents was negligible.

PHOTO 15. Cooling tower on steel frame provided for future roof. See also photo 16, Penney's Store, Daly City.

Photo 16. Detail of leg failure of cooling tower shown in photo 15. Note excessive number of bolt holes.

Photo 17. Damaged building at Colma. Compare with plate 95A of volume I of *The California Earthquake of April 18, 1906*, Carnegie Inst. Wash., 1908.

finish. Inside the store, mechanical equipment shifted on the mezzanine floor, and goods shifted on the shelves, but the earthquake loss to contents was probably limited to a relatively negligible $200.

A cooling tower (photo 15) is located on top of the steel framing for the future roof. As shown in photo 16, the legs failed at a point of high moment which was also the location of an excessive number of bolt holes. Elsewhere, a cast-iron clip broke at the connection of the cooling tower leg to its support.

Colma and Lake Merced. The most seriously damaged masonry building known to the authors is in the nearby city of Colma (photo 17). Incidentally, only a few of the nearby tombstones shifted or turned over.

Large wood frame structures had damage patterns similar to wood frame dwellings. For example, the main

Photo 18. Broken masonry veneer, Stonestown Shopping Center, Lake Merced district of San Francisco. Building resisted lateral forces by column bending. See also photo 19.

Photo 19. Tablecloth caught between panes of glass as building moved back and forth during earthquake. While veneers and windows cracked, remarkably little merchandise fell from shelves. Stonestown Shopping Center. *Photo by Wide World.*

PHOTO 20. Looking down an escalator, Emporium Department Store, Stonestown Shopping Center. Ceiling shifted, causing damage at rigid elements such as escalator walls.

three-story building for the Olympic Club, located on the golf course at the San Francisco-San Mateo County line, had no significant structural damage. Only one plate glass window broke; plaster cracking was more noticeable in the first and second stories, and the three brick chimneys tended to separate from the building. At the nearby Starter House, about 50 roof tile were shaken loose, but none shifted far enough to fall from the roof. Interestingly, no glassware or liquor stocks were lost in any of the dining rooms or bars, according to the local management.

The Emporium Department Store building in the Stonestown Shopping Center is two and three stories in height. It has a ground-floor area of about 87,000 square feet and is roughly rectangular in plan. Lateral forces are resisted by means of reinforced concrete shear walls. Brick and stone veneers, anchored to the concrete backing walls, were not damaged. The suspended ceiling on one floor shifted back and forth, causing damage along its wall boundaries and at such rigid elements as escalators (photo 20) and partitions. Contents loss in the building was negligible. A concrete slab cracked at the southeast corner, but this was probably due to a poorly compacted local backfill.

The foregoing examples are typical of other structures examined in and around the field epicentral region. All buildings which were discussed had lateral force resisting elements to some degree, except the structure in Colma. All had reinforced concrete spread footings or belled caissons drilled and cast in place. Foundation material was sand, silty sand, or lightly cemented sandstone. Glass breakage, partitions cracks, and veneer damage were common in the flexible buildings, but considerably less so in the rigid buildings. No damage pattern by class of construction material was observed in earthquake-resistant buildings, and this of course is consistent with theory. It should also be added that the earthquake was too weak to test certain building-material assemblies which are currently in question.

Other Areas. The extent of glass breakage and plaster cracking diminished with distance from the field epicenter. Some existing plaster cracks were reopened or extended. In many instances, occupants examined structures after the earthquake and incorrectly identified cracks formed years ago as results of the present earthquake. Several instances of damage, of the many that did occur, are of interest.

The Academy of Sciences building in Golden Gate Park in San Francisco had slight plaster damage. Damage occurred to the curved painted plastered walls around the stuffed animal displays ("dioramas"). The repair of the slight cracking and spalling of the plaster required meticulous workmanship, and the loss has been estimated at $5000.

The United Greek Orthodox Community Church, located at 245-51 Valencia Street in San Francisco, had plaster damage at the juncture of the first and second story ceilings with their rear wall boundaries. Partition wall cracking was also noted in the rear in the former stage area. This church, a remodeled theater originally built in 1907, has steel columns, steel beams, and steel roof trusses, with 17″ brick panel walls. The building is about 76 feet by 147 feet in plan, and the height to the truss line is 45 feet. The second floor, of wood frame construction on steel beams, was added near mid-height during a remodeling. Cracking in this church appears to have been greater than average for its class of construction, although no structural failures were noted. It is

PHOTO 21. Damage to Detail 1, figure 7.

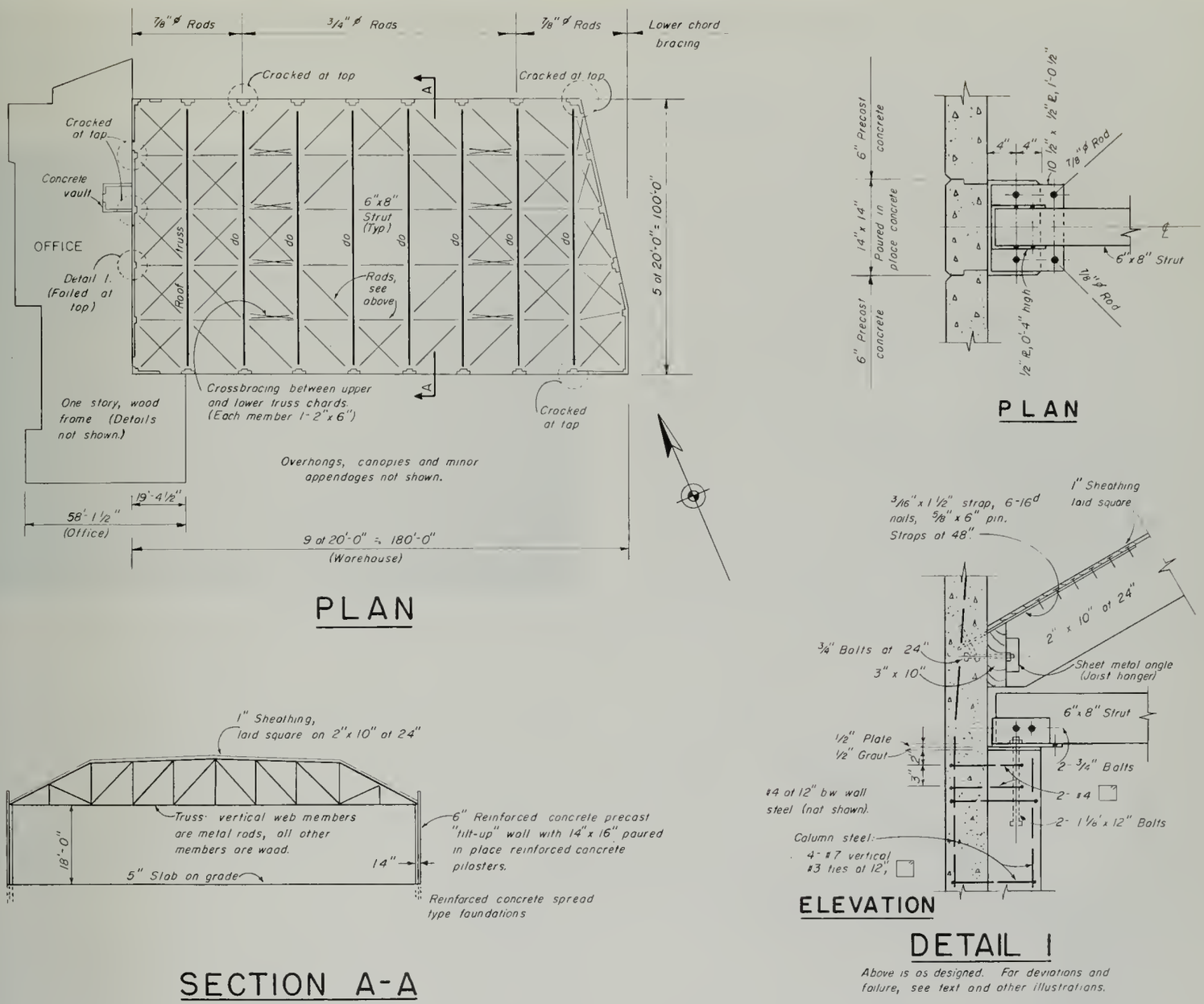

7/8" ø Rods
3/4" ø Rods
7/8" ø Rods
Lower chord bracing
Cracked at top
Cracked at top
Cracked at top
Concrete vault
OFFICE
Detail 1. (Failed at top)
Truss
Roof
do
6"x8" Strut (Typ)
Rods, see above
5 at 20'-0" = 100'-0"
Crossbracing between upper and lower truss chards. (Each member 1-2"x6")
Cracked at top
One story, wood frome (Details not shown.)
Overhongs, canopies and minor appendages not shown.
19'-4 1/2"
58'-1 1/2" (Office)
9 at 20'-0" = 180'-0" (Warehouse)
PLAN
6" Precost concrete
14" x 14" Poured in place concrete
6" Precost concrete
4"
4"
10 1/2" x 1/2" ℄, 1'-0 1/2"
7/8" ø Rod
6"x8" Strut
7/8" ø Rod
1/2" ℄, 0'-4" high
PLAN
1" Sheathing, laid square on 2"x10" at 24"
Truss: vertical web members are metal rods, all other members are waad.
18'-0"
5" Slab on grade
6" Reinforced concrete precast "tilt-up" wall with 14"x16" paured in place reinforced concrete pilasters.
14"
Reinforced concrete spread type foundations
SECTION A-A
3/16"x1 1/2" strap, 6-16d nails, 5/8"x6" pin. Straps at 48".
1" Sheathing laid square
2" x 10" at 24"
3/4" Bolts at 24"
3" x 10"
Sheet metal angle (Joist hanger)
6"x8" Strut
1/2" Plate
1/2" Grout
2-3/4" Bolts
#4 at 12" bw wall steel (not shown).
2-#4
2-1 1/8"x12" Bolts
Column steel: 4-#7 vertical #3 ties at 12"
ELEVATION
DETAIL 1
Above is as designed. For deviations and failure, see text and other illustrations.

FIGURE 7. Plans, section, and elevation of Office and Warehouse building, Bayshore.

possible that the damage may be related to the relatively flexible construction of the original building, with the subsequent interior partition and floor and ceiling construction representing nonstructural rigid elements and, therefore, readily damageable features.

Winterland Auditorium, at the northwest corner of Post and Steiner Streets in San Francisco, is 137'–6" by 275'–0" in plan and is essentially a very tall one story structure. The high point of the roof is about 75 feet above the sidewalk level. The roof is 3 inch wood plank on steel arched trusses spanning across the building, with the trusses in turn supported on steel columns. Walls are 6 inch reinforced concrete and are nonbearing in the steel frame. Partitions above the first floor are located in the ends in order to allow for a maximum auditorium area. Lateral forces are taken by means of a rod bracing system in the longitudinal direction and by the columns in bending in the transverse direction. The structure, built in 1929, was probably designed to resist nominal wind forces Damage again was nonstructural and was confined to plastered walls and the concrete wall boundaries of the main suspended ceiling.

Two buildings with freshly poured concrete were examined by the authors. A large reinforced concrete wall in the California Masonic Memorial Temple Building at California and Taylor Streets in San Francisco was poured the morning of the shock. Careful inspection found no visual defects. In Santa Rosa the concrete roof slab for the new Sonoma County Administration Building was about 4 hours old at the time of the earthquake. Visual inspection indicated two areas which had an abnormal amount of cracking, possibly due to the earthquake. A subsequent load test program indicated that the concrete was sound.

Office and Warehouse Building, Bayshore. Minor but interesting damage occurred to a building located in Bayshore, a community just south of the San Francisco city limits. The building has a one-story office area which is of wood frame construction and is structurally tied to the warehouse. Both the office and warehouse were built

in 1953. The roof over the office is lower than the warehouse roof. A description of the warehouse construction may be found in figure 7.

Minor plaster cracking occurred to the partitions in the office area. This type of damage was particularly noticeable at the juncture of the reinforced concrete vault to the wood framing above the vault.

In the warehouse, a rod bracing system in the plane of the bottom chord of the trusses was designed to resist lateral forces. The concrete columns and walls take the earthquake forces from the rod bracing system to the ground.

Damage within the warehouse occurred at six locations. The most pronounced damage was at Detail 1 in figure 7 (see also photo 21). The grout is gone, and the anchor bolts, which were not set vertically, moved from their original position in the concrete. The plate beneath the strut moved away from the wall (as evidenced by the paint on the plate beneath the strut). No evidences of unusually high stresses were noted elsewhere in the joint assembly.

In comparing Detail 1 of figure 7 with photo 21, it may be observed that the column reinforcing steel, the column ties, and the two extra #4 ties around the anchor bolts do not show. Upon repair of this and the other five locations, actual construction was found to be as in figure 8.

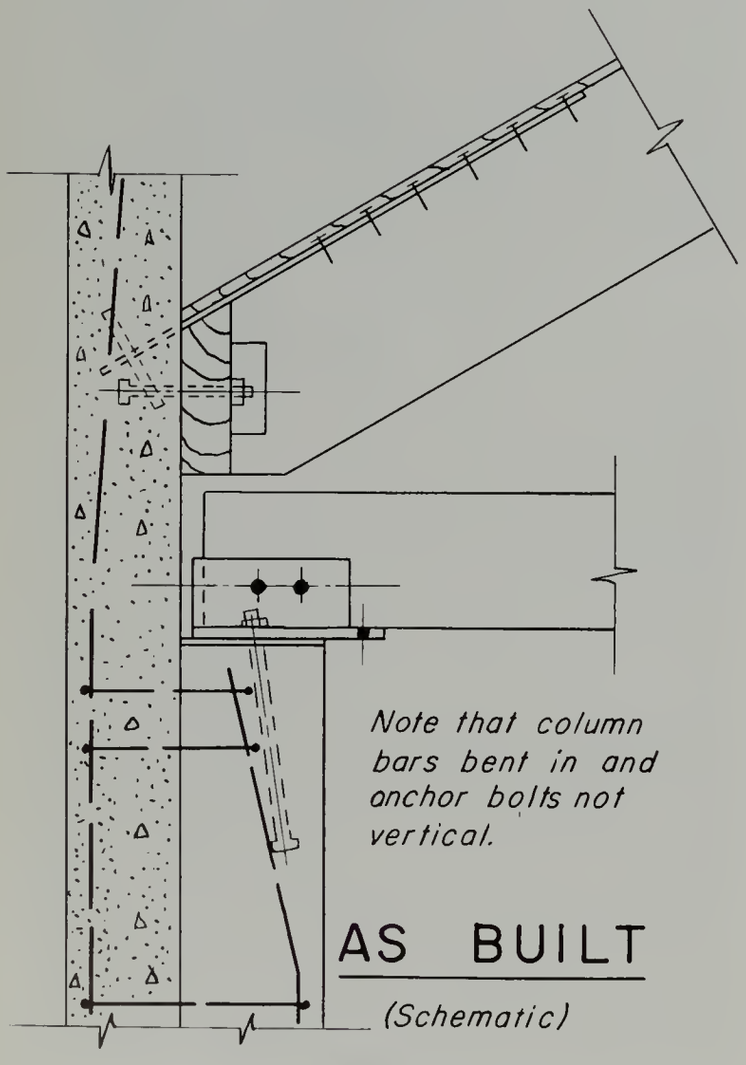


FIGURE 8. "As built" construction of Detail 1, figure 7.

The other damaged locations were at the tops of five concrete columns which cracked, but did not spall. This damage was not noticed until several days after the earthquake, but it appears to be attributable to earthquake forces.

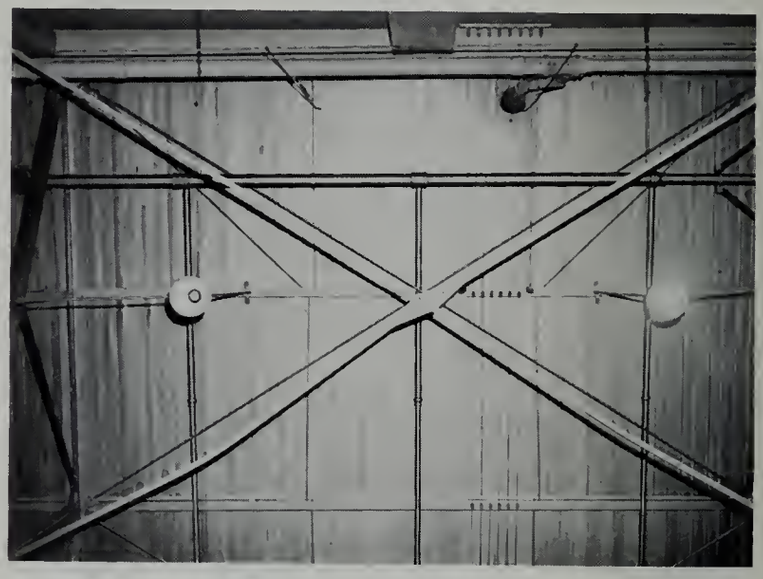


PHOTO 22. Looking up at buckled X-bracing in Hanger 13 at United Air Lines Maintenance Base. *Photo by United Air Lines.*

San Francisco Airport. The San Francisco International Airport is located about 10 miles southeast of the epicentral region. The airport is on the mud flats which surround large areas of San Francisco Bay. On this structurally poor ground major buildings must usually be built on piling. At the airport, differential settlement between buildings on piling and the adjoining ground surface can be measured in terms of feet. This has necessitated extra steps on stairs and considerable maintenance at the entrances to garages, etc.

Buildings at the airport are of various types of construction; most of them have been built within the last 15 years. A plot plan of the buildings and underground water lines is shown in figure 9. Most buildings have strong lateral-force bracing systems. None of the normally earthquake-collapse-hazard type of construction, such as unreinforced sand-lime mortar brick bearing wall construction or its counterpart in hollow concrete block, exists at the airport.

Underground water lines were damaged at six locations (which may be compared to the Daly City region, which had only three reported underground water-line breaks). The airport also had one gas-line break. Data are incomplete on some of the breaks at the airport, but the gradual differential ground settlements, accentuated by the earthquake, undoubtedly played a part. For example, breaks at location C-5 and D-1 in figure 9 are clearly attributable to differential settlements. It is quite possible that the gas-line damage could have been prevented if an oversize sleeve had been put around the pipeline where it went through the wall. Breaks C-3 and C-4 were corroded, and the earthquake was merely the "trigger" in causing the breaks.

Some indication of the settlement problems related to underground pipelines may be had from the experience at Pan American World Airways. This facility, largely

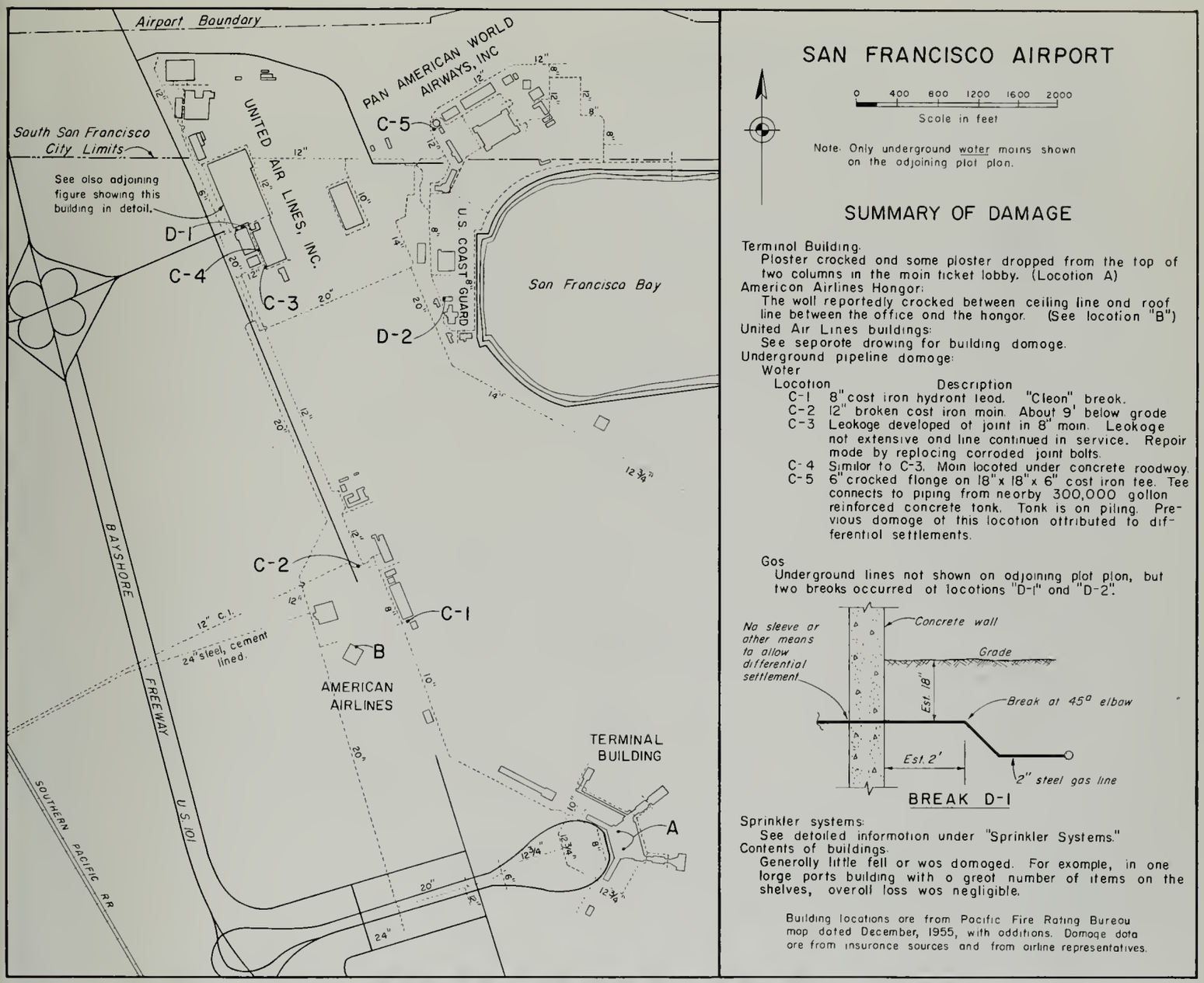

Airport Boundary
PAN AMERICAN WORLD AIRWAYS, INC
UNITED AIR LINES, INC.
South San Francisco City Limits
See also adjoining figure showing this building in detail.
D-1
C-4
C-3
C-5
D-2
U.S. COAST GUARD
San Francisco Bay
C-2
C-1
B
AMERICAN AIRLINES
TERMINAL BUILDING
A
BAYSHORE FREEWAY U.S. 101
SOUTHERN PACIFIC RR
12" C.I.
24" steel, cement lined.
SAN FRANCISCO AIRPORT
0 400 800 1200 1600 2000
Scale in feet
Note: Only underground water mains shown on the adjoining plot plan.
SUMMARY OF DAMAGE
Terminal Building.
Plaster cracked and some plaster dropped from the top of two columns in the main ticket lobby. (Location A)
American Airlines Hangar:
The wall reportedly cracked between ceiling line and roof line between the office and the hangar. (See location "B")
United Air Lines buildings:
See separate drawing for building damage.
Underground pipeline damage:
Water
Location Description
C-1 8" cast iron hydrant lead. "Clean" break.
C-2 12" broken cast iron main. About 9' below grade
C-3 Leakage developed at joint in 8" main. Leakage not extensive and line continued in service. Repair made by replacing corroded joint bolts.
C-4 Similar to C-3. Main located under concrete roadway.
C-5 6" cracked flange on 18"x 18"x 6" cast iron tee. Tee connects to piping from nearby 300,000 gallon reinforced concrete tank. Tank is on piling. Previous damage at this location attributed to differential settlements.
Gas
Underground lines not shown on adjoining plot plan, but two breaks occurred at locations "D-1" and "D-2".
No sleeve or other means to allow differential settlement
Concrete wall
Grade
Est. 18"
Break at 45° elbow
Est. 2'
2" steel gas line
BREAK D-1
Sprinkler systems:
See detailed information under "Sprinkler Systems."
Contents of buildings.
Generally little fell or was damaged. For example, in one large parts building with a great number of items on the shelves, overall loss was negligible.
Building locations are from Pacific Fire Rating Bureau map dated December, 1955, with additions. Damage data are from insurance sources and from airline representatives.

FIGURE 9. Damage at San Francisco airport.

built in 1944, has had an estimated 40 pipeline breaks, most of them in the first 3 years. The last 5 years have averaged about two breaks a year. All of their underground lines are cast iron.

Considering the past history of pipe breakage, underground pipeline damage at the airport was nominal during this earthquake. Much more extensive damage is likely in a major shock of long duration (Schussler 1906; Steinbrugge and Moran 1957).

Some relatively minor, but interesting, damage occurred to the United Air Lines structures. An outline of some of the buildings plus some structural information is shown in figures 10 and 11.

Building 15 (center) has a reinforced concrete flat slab second floor, and has steel frame sawtooth roof construction. The roof deck is metal. All east-west lateral forces are taken primarily by column bending. Building 15 (center) is to a great extent structurally independent of 15 (south), while it is completely independent of 15 (north). The second floor of Building 15 (center) is a continuous concrete slab and will act as a rigid unit; however, the sawtooth roof construction can allow some differential movement between structural elements. Building 15 (center) is quite flexible as compared to the rigid elements in many of the neighboring buildings. It also can have relatively large torsional deflections for north-south forces.

Some cracking of nonbearing hollow concrete block partitions occurred throughout the center and south sections of Building 15, with perhaps relatively lesser damage noted in 15 (north). Damage occurred to north-south as well as east-west hollow concrete block partitions, and was observed in the first story as well as in the second story. At several places, the roof over the second floor moved with respect to the top of the hollow concrete block walls, attesting to the deflections taking place in the second story. Some fresh diagonal cracks were noted in the reinforced concrete shear walls of Building 15

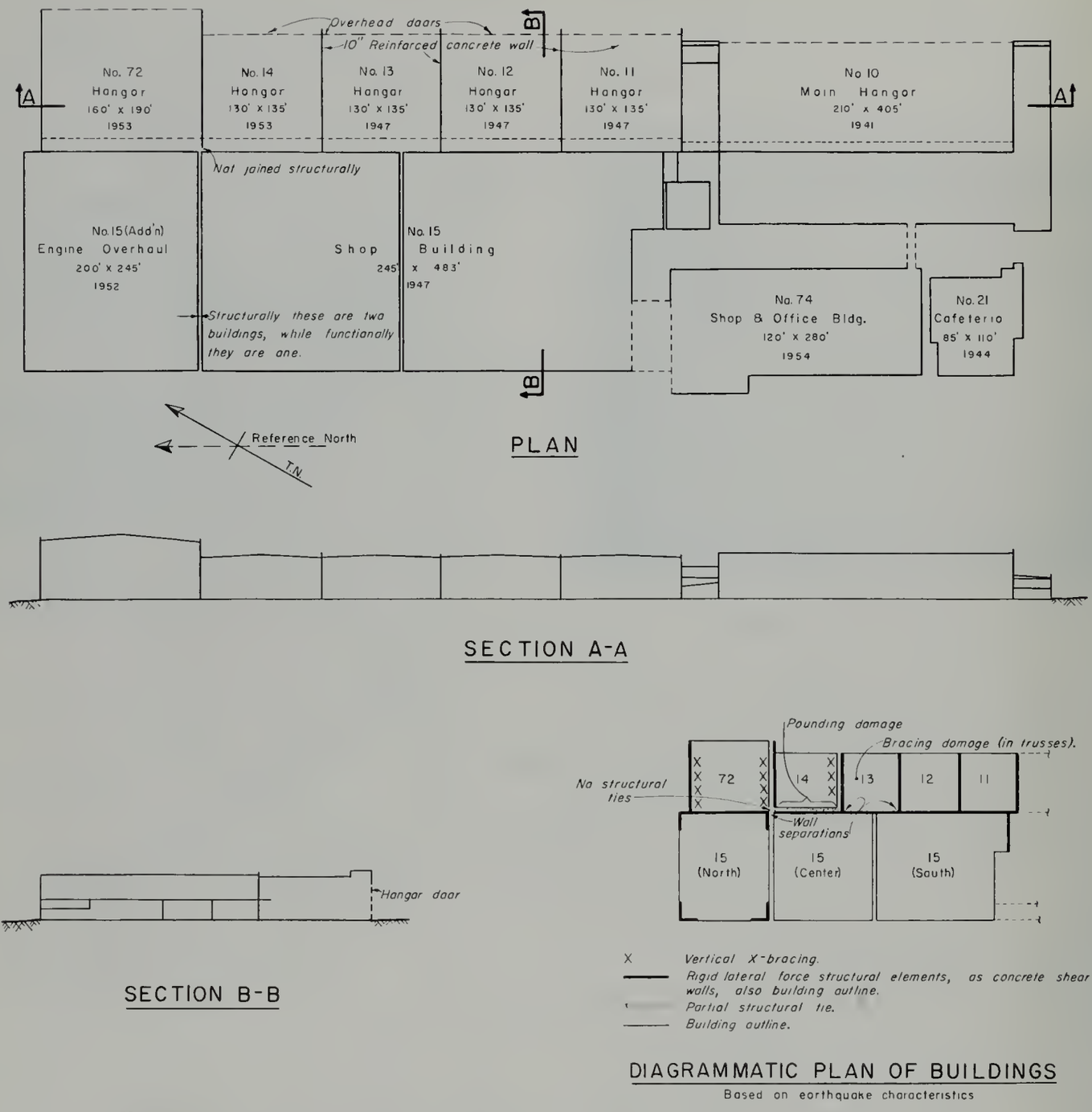

Overhead doors
10" Reinforced concrete wall
No. 72 Hangar 160' x 190' 1953
No. 14 Hangar 130' x 135' 1953
No. 13 Hangar 130' x 135' 1947
No. 12 Hangar 130' x 135' 1947
No. 11 Hangar 130' x 135' 1947
No. 10 Main Hangar 210' x 405' 1941
Not joined structurally
No. 15(Add'n) Engine Overhaul 200' x 245' 1952
Shop 245'
No. 15 Building x 483' 1947
Structurally these are two buildings, while functionally they are one.
No. 74 Shop & Office Bldg. 120' x 280' 1954
No. 21 Cafeteria 85' x 110' 1944
Reference North
T.N.
PLAN
SECTION A-A
Hangar door
SECTION B-B
Pounding damage
Bracing damage (in trusses).
No structural ties
Wall separations
15 (North)
15 (Center)
15 (South)
X Vertical X-bracing.
Rigid lateral force structural elements, as concrete shear walls, also building outline.
Partial structural tie.
Building outline.
DIAGRAMMATIC PLAN OF BUILDINGS
Based on earthquake characteristics

FIGURE 10. Outline of United Air Lines Maintenance Base structures, San Francisco airport.

(north) as well as along one construction joint, but some of the diagonal cracking may have existed before the earthquake.

Some of the X-bracing in the plane of the lower chords of the roof trusses buckled in several hangars:

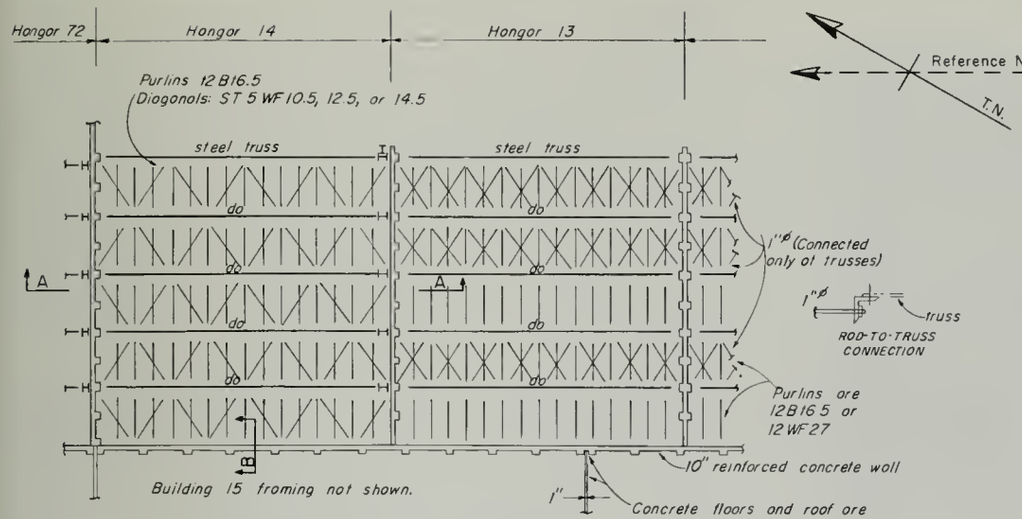
Hangar 12: All buckled along north side at concrete wall.

Hangar 13: All buckled along north and south sides at the concrete wall. Buckling damage most pronounced in this hangar. See photo 22.

Hangar 14: Reported to have buckled along north and south sides at the concrete wall. This report could not be confirmed.

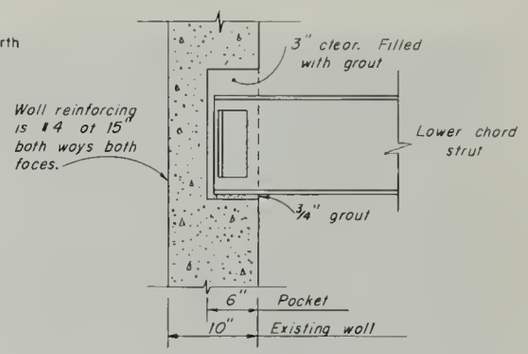
The trusses and their other bracing members did not show evidences of distress.

The channels, which buckled in the X-bracing system, are acceptable as tension members but are deficient in compression. In this case, their ratio of length to least radius of gyration was nearly 350. Conventionally, a lateral force bracing system is designed as a statically determinate system, with the diagonal bracing assumed to be effective for tension only. However, as the tension members elongate and the panel around each tension member distorts, compressional forces will occur in the neglected member (which is along the other diagonal) if the latter member is rigid. Once loaded in compression beyond the buckling load, the channel could keep its buckle through subsequent elongations and shortenings, as long as the entire cross section of the member would not be stressed beyond the yield point in tension. The foregoing discussion may be more easily understood if a panel with X-bracing is drawn and then distorted, keeping in mind that the diagonal in compression is weak.



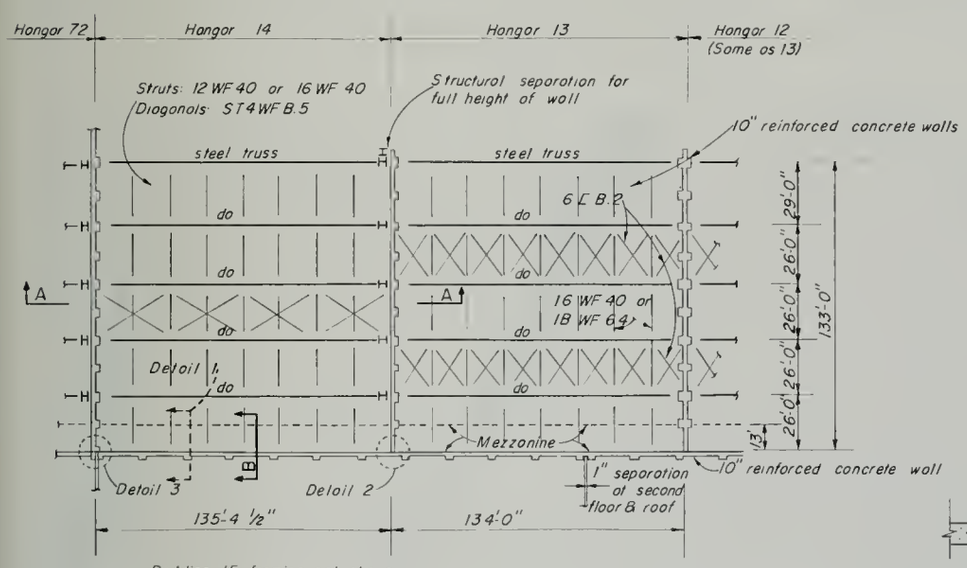
UPPER CHORD FRAMING

(For Hangars 13 and 14)



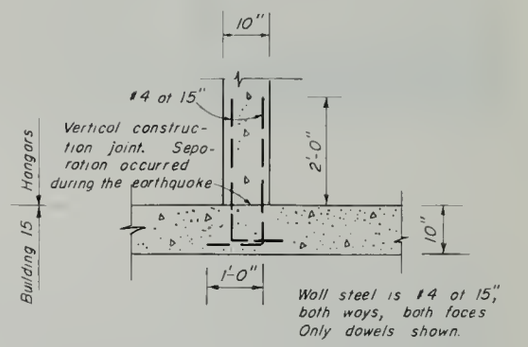
DETAIL 1

Detail of anchorage of beams to existing wall of Building 15.



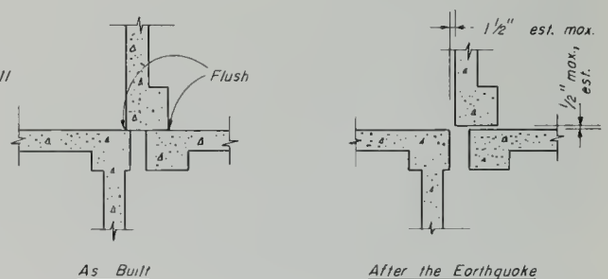
LOWER CHORD FRAMING

(For Hangars 13 and 14)



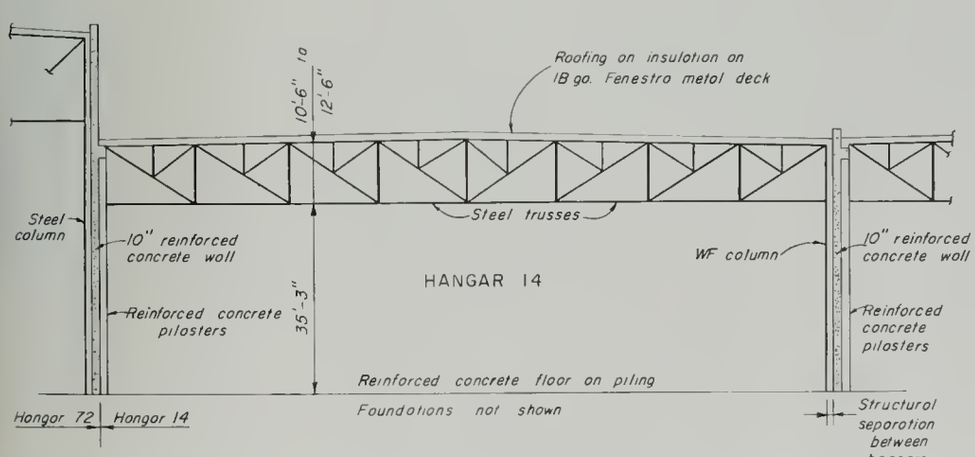
DETAIL 2

Typical wall intersection except where otherwise shown.

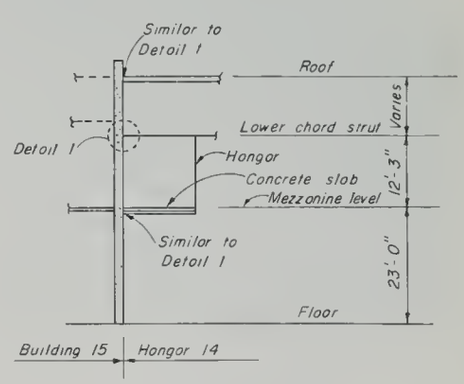


Separations increased with height. Some separations occurred prior to shock.

DETAIL 3



SECTION A-A



SECTION B-B

FIGURE 11. Some construction details, United Air Lines Maintenance Base, San Francisco.

PHOTO 23. Damage at Detail 1, figure 11. *Photo by United Air Lines.*

The north walls of Hangars 13 and 14 separated from Building 15, as indicated in Details 2 and 3 of figure 11. In addition to the wall separation, beams at the mezzanine level, struts from the lower chords, and purlins at the roof level separated from the west wall in Hangar 14 (see fig. 11, photos 23 and 24). The maximum pull-out of beams from the wall is estimated at around 1 inch. Some slight separation also occurred between the north wall of Hangar 12 and the east wall of Building 15. The size of the wall separation became larger in the following order: Northwest corner 12, northwest corner 13, northwest corner 14.

Differential settlements also probably are a factor in the observed damage. Some of the separation at the northwest corner of Hangar 14 probably existed prior to the earthquake, as traces of paint were found in the crack. The wall separation tended to increase in size as it went up toward the roof—a type of separation often associated with settlement. The fact that the north wall of Hangar 14 was structurally separate from Building 15 could facilitate differential settlements. It should be added that vertical construction joints occurred where the other separations were observed, and that the buildings are all on piling.

PHOTO 24. Photograph of damage to wall connections at mezzanine (Section B-B, fig. 33). Note that bolts are loose. *—Photo by United Airlines.*

Some indication of soil conditions at this building may be obtained from the following boring log:

+5.26* to —17:	Soft gray organic silty clay (bay mud).
—17 to —20:	Green silty clay. Firm brown and gray clay.
—20 to —22:	Firm sandy clay, some gravel.
—22 to —28:	Firm brown very fine silty sand.
—28 to —33:	Soft gray silty clay and sand (like bay mud).
—33 to —43:	Firm dark gray silty sand and clay. Firm gray silty very fine sand.
—43 to —48:	Soft green-gray silty clay.
—48 to —52:	Firm green-gray, clayey sand.
—52 to —61:	Firm gray-brown silty clay, some sand lenses.
—61 to —66:	Hard brown silty very fine sand.

*Ground surface. Elevations in feet.

The earthquake was not of major intensity at the airport, but did appear to be heavier than at nearby areas on firm ground.

MISCELLANEOUS STRUCTURES

Sewage Treatment Plants

Damage to pipes occurred to the San Pedro Sewer and Maintenance District's plant located on the ocean front in the Linda Mar-Pedro Valley region. The plant, in general, is typical of other recently built sewage-treatment plants. All structures are poured-in-place reinforced concrete and are founded on piling.

The buildings suffered no damage. A 6-inch cast-iron sludge recirculating pipe from the circular 35-foot inside diameter digestor separated as shown in photo 25. A nearby water line also broke. Ground around the structures settled prior to the earthquake as well as during the earthquake, but the relationship between these settlements is not known. A log of the deepest nearby boring is given in table 2.

Photo 25. Pipeline damage at San Pedro Sewer and Maintenance District's plant.

Table 2. Boring log at San Pedro Sewer & Maintenance District's plant. Distances in feet

0 to —3.5:	Organic clay
—3.5 to —16.0:	Peat
—16.0 to —18.0:	Organic clay, blue
—18.0 to —28.0:	Sandy clay, stiff
—28.0 to —40.0:	Firm clayey sand

The North San Mateo County Sanitation District plant is located in Daly City and is slightly northeast of the junction of Alemany and Lake Merced Boulevards. The Office and Control Building is one story plus basement, and is of reinforced concrete construction. A nearby 1,000,000-gallon sludge digestor is 75 feet inside diameter and extends 10 feet below finish grade. All structures rest on heavy reinforced concrete spread foundations. This plant was built in 1954-55. Ground around the building settled from $\frac{1}{2}$ inch to $1\frac{1}{2}$ inches; much of this is known to have resulted from the earthquake. Settlement around the digestor was noted, but the amount of settlement during the earthquake, if any, is unknown. Settlement appears to be confined to the local backfills. No piping damage occurred. Some minor nonstructural partition damage was noted in the Office and Control Building. As of April 25, 1957, there were no known instances of sewer-line damage in Daly City which could be attributed to the shock.

Elevated Tanks

It is estimated that several hundred buildings in San Francisco have elevated roof tanks in connection with their sprinkler systems. In addition, there is an unknown number of small roof tanks used in connection with domestic water supplies.

No tanks are known to have collapsed. For that matter, the authors have no positive record of any roof tank having shifted on its supports, even when not anchored. In one instance the considerable leakage which occurred may be attributed to a severely rust-weakened area on the tank, from which the parent metal was entirely gone. In another instance, leakage occurred at the discharge connection of a wood tank; it may be that the leakage was the result of improper repairs which had been completed just prior to the earthquake, or due to a slight rocking of the tank whose height exceeded its diameter, or both.

Tank at Army and Mission Streets, San Francisco. A 2-inch drain pipe on a 50,000 gallon steel tank broke. The tank being 21 feet 3 inches in diameter by 21 feet high, used to supply sprinklers, was in an enclosed concrete tower on the roof of a three-story reinforced concrete frame building. The structure was built about 1928. In 1933 or 1934 earthquake bracing was added to the tank by means of 16 equally spaced springs as shown in figure 12, and some flexibility was added to the piping.

The 2-inch drain pipe broke at its connection to the tank, but other piping was undamaged. The undamaged piping had flexible connections well located, and no evidences of high stress were observed. As shown in figure 12, the pipe that broke had a sleeve which would allow 3-inch movement in either direction along the pipe. However, this particular type of connection allowed for very little horizontal or vertical movement at right angles to the pipe axis. It seems unlikely that the tank shifted back and forth, for the observed earthquake intensity at

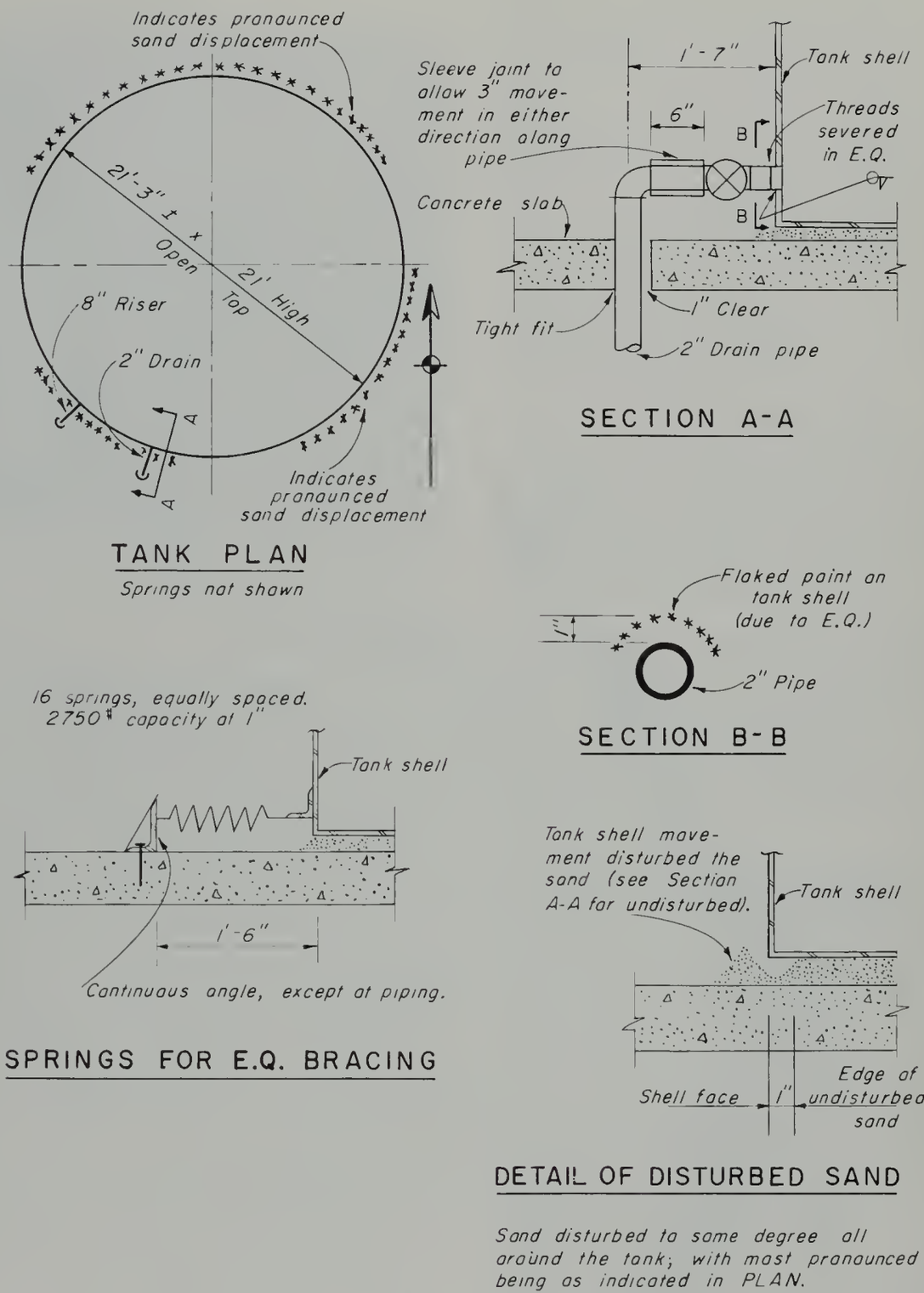
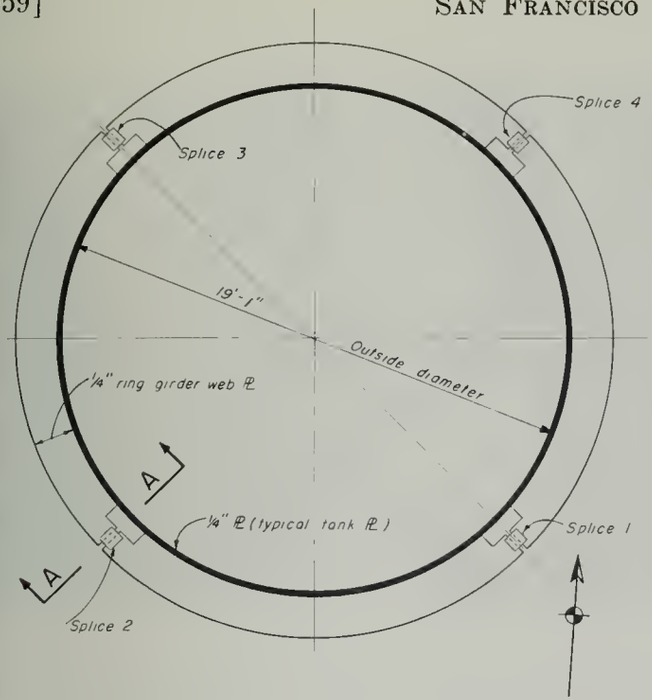


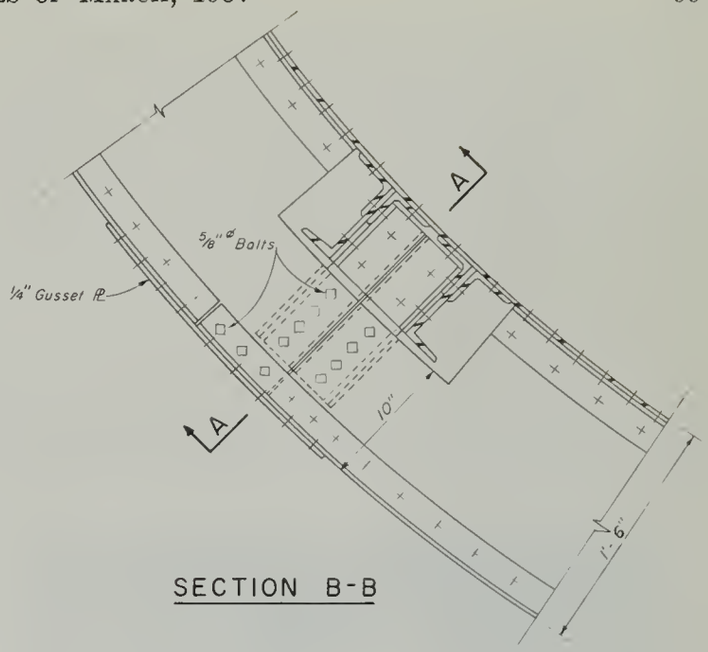
FIGURE 12. Roof tank near Army and Mission Streets, San Francisco.

this location gave no such indication. A more probable cause of breaking was the tank shell distortions which accompanied the water wave motion in the tank. Wave action can lift or depress that portion of the tank shell adjacent to the tank axis perpendicular to the direction of wave motion. The observed earthquake effects support this explanation. First, the disturbed sand base indicates vertical shell movement. Second, the pipe broke at a theoretically highly stressed point for vertical motion. In addition, the flaked paint on the shell (Section B-B, fig. 12) is consistent with this view. Similar effects were noted at two California Water Service Tanks (see the section on *Public Utilities*, this report).

The fact that the 2-inch pipe was tight against the concrete may be attributed to the effects of water pressure on the expandable sleeve; this movement could occur whenever the tank was drained. The earthquake caused an estimated $5,200 in plaster damage at various locations throughout the building. In many cases the damage occurred to old cracks which had been repainted prior to the earthquake.



PLAN SECTION AT BALCONY GIRDER

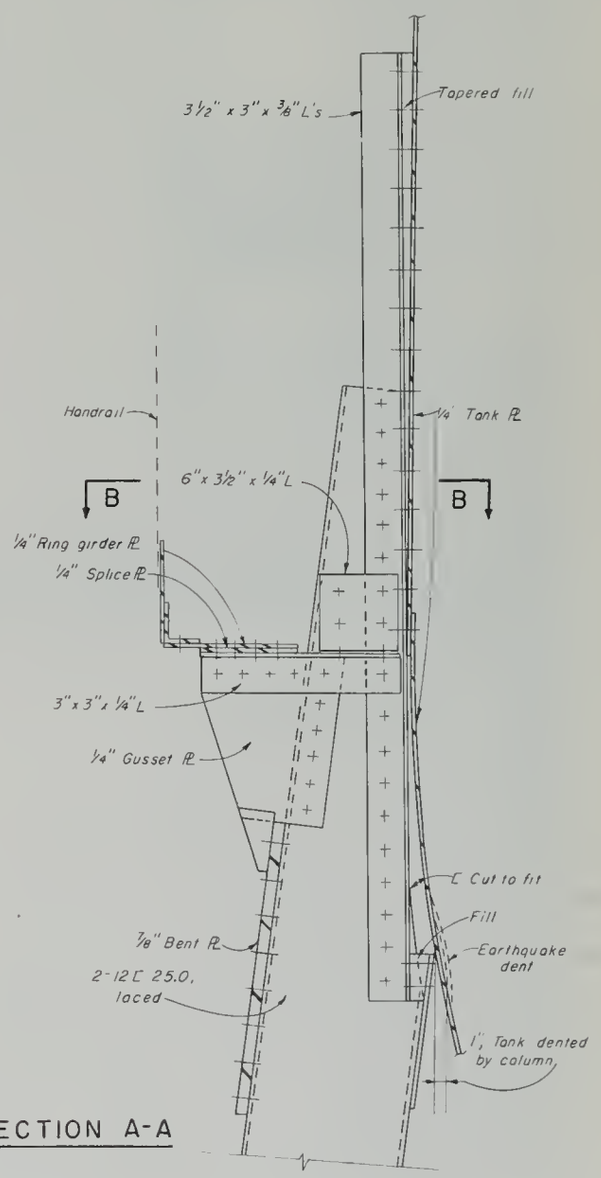


SECTION B-B

DAMAGE TO BALCONY GIRDER

Splice	Comments
1.	All 8 splice plate bolts in at time of earthquake. Connection failed. Splice plate corroded to half thickness in some places.
2.	Apparently only one splice plate bolt in at time of earthquake. Reason for this bolt failure unknown. See photograph.
3.	Four splice plate bolts in on one side of the splice; one bolt in on the other side. All bolts sheared.
4.	All bolts in and splice plate held. Bolts showed signs of high stress

Notes: Corrosion weakened all joints.
Connection failure was due to shearing of bolts.



SECTION A-A

FIGURE 13. Some construction details of roof tank at Folsom and 15th Streets, San Francisco.

Tank at Folsom and Fifteenth Streets, San Francisco. Another instance of interesting damage oeeurred to a steel sprinkler tank located on the roof of a six-story reinforeed concrete frame warehouse. The building walls are 13-inch brick panel, unreinforced except for some steel dowels from the reinforeed concrete eolumns into the brickwork. Foundation conditions are poor, and the building rests on piling. Some slight nonstructural eracking was noted in the building after the earthquake. Stocks of merchandise did not fall.

The 50,000-gallon elevated roof tank appears to have been built on a 100-foot steel tower at this site in 1922. About 1927 the legs were shortened to 35 feet and the tank was placed on the roof of the present building. In 1933 the tank was strengthened to resist 15 percent G lateral forces (photo 26).

PHOTO 26. A seriously damaged 50,000 gallon roof tank, Folsom and Fifteenth Streets, San Francisco. See also figure 13, photos 27, 28.

After the earthquake the tank was leaking, the rods in the upper panels were slack, the tank shell was dented at the columns, and bolts were out of the splices of the balcony girder.

Corrosion was severe. Paint crews had repeatedly painted over the rust.

Failures occurred to the balcony girder spliees (Section B-B of figure 13), but not to the splices in the outside angle. Photo 27 shows that the inside angle was not continuous at the columns. Bolts were missing in the splice plates prior to the earthquake. Slight buckling of the balcony girder was noted at several locations near the splice plates. The failed splices are at locations of high earthquake stresses, as the vertical rod bracing eonnection is nearby. The combination of eorrosion, missing bolts, and stress concentration probably explains

PHOTO 27. Tank detail shown in Section B-B of figure 13. Note that bolts in splice were not in when tank was last painted.

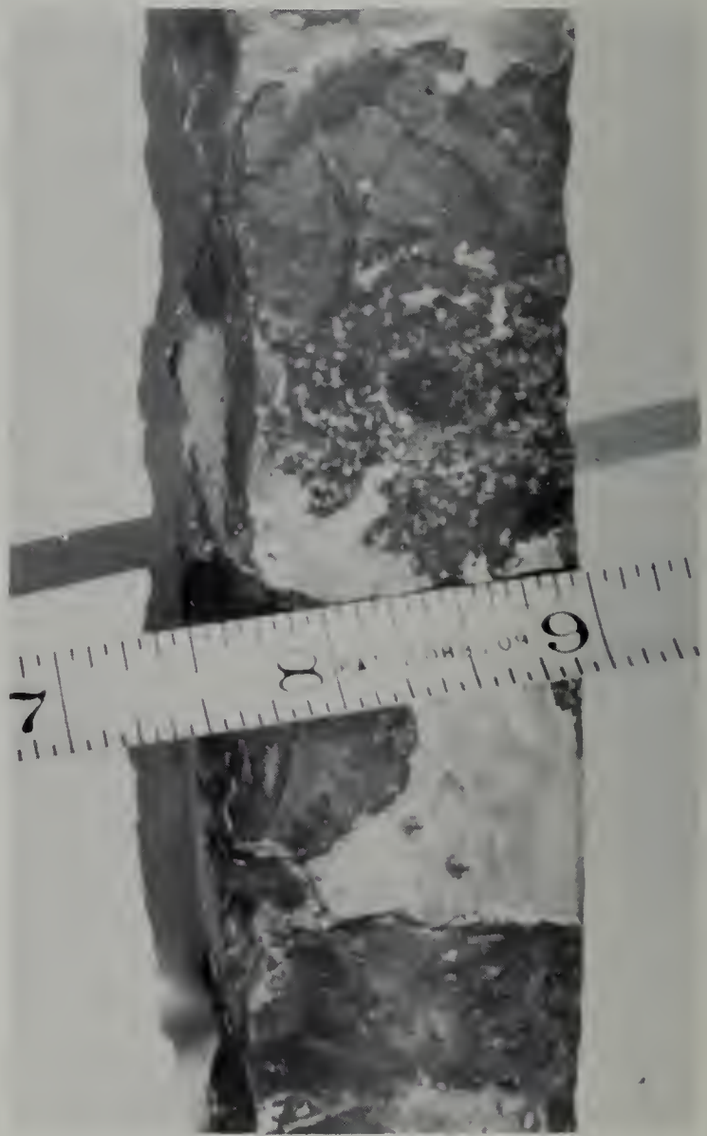


PHOTO 28. Corrosion-weakened rod from upper panel of tank in photo 26.

why this is the only tank of its type known to have been damaged. The possibility of the rods being slack prior to the earthquake should not be overlooked; this would add heavy impact stresses to the splice.

The tank may have rocked on top of its legs, for the tank shell was dented as shown on the drawing in figure 13. It is also possible that the dents resulted from the loosening of the connection at the top of the column.

Elevated Ground Tanks

The authors have no record of damage to elevated tanks located on ground, whether braced to resist strong seismic forces or not. The elevated steel tank nearest to the epicenter is a tank of 100,000-gallon capacity on a 50-foot steel tower. This tank, at the Lake Merced Golf and Country Club adjoining Daly City, was not designed to resist earthquake. Rod bracing connections were rusted. However, no evidence of high stresses was noted.

Golden Gate Bridge

The Golden Gate Bridge is a suspension bridge between San Francisco and Marin Counties. Its single deck carries a total of six lanes of highway traffic. The center span distance is 4,200 feet and each of the side spans is 1,125 feet. The bridge is founded on rock. Earthquake forces were given consideration in the original design (Golden Gate Bridge and Highway District, 1937). This structure is of interest in that it is the longest clear span suspension bridge in the world and is located about 7 miles north of the epicenter of the main shock.

The following information is based on a *Report on the San Francisco Earthquake of March 22, 1957, as Related to the Golden Gate Bridge,* June 1957, by Golden Gate Bridge and Highway District.

A detailed examination of the bridge was made immediately after the shock. No damage occurred to the bridge. About 20 windows broke in the toll booths south of the bridge and a few panes broke in the Administration Building; no structural damage was involved. Traffic flow on the bridge was not interrupted, and motorists did not report feeling any movement. Painters on the road deck at the north tower reported feeling the bridge shake and noted that the cables swayed for a few seconds. No painters were on the towers during the earthquake.

Six instruments, located on the bridge deck, record the vertical motions of the bridge. The Bridge District's Consulting Engineer, Clifford E. Paine, reported as follows after viewing the instrumental record:

"Instrument number 1 is at the center of the San Francisco Side Span. The double amplitude of record is 0.49 inch. The period of vibration is 3.5 seconds. The impressed vibration which would yield the above instrument recording is 5.6 inches. This is the vertical double amplitude obtained at the middle of the San Francisco Side Span.

"Instrument number 5 is at the center of the Main Span. The double amplitude of record is 0.25 inch. The period of vibration is 3.33 seconds. The impressed vibration which would yield the above instrument recording is 2.9 inches. This is the vertical double amplitude at the middle of the Main Span.

"The discussion is limited to instruments numbered 1 and 5 because charts from the other instruments contribute no pertinent, additional information."

The foregoing vertical motion is negligible as compared to the 130 inches double amplitude motion recorded on the main span in the windstorm of December 1, 1951. No instruments record the bridge's horizontal motion.

PUBLIC UTILITIES

Water

Daly City. The damage to the Daly City water system was confined to the Westlake Palisades area. Three water lines broke: an east-west 6-inch transite line on south side of Seacliff Avenue, in which the pipe telescoped, indicating ground shortening; a 2-inch east-west galvanized line on north side of Seacliff Avenue, which cracked through the threads, with indications of compressive forces; and a third similar to the 2-inch line on Seacliff Avenue. The foregoing damage is interesting because of its relation to nearby ground-surface effects and dwelling damage.

One of Daly City's reservoirs, located at the highest point of the Westlake Palisades tract, cracked and leaked as a result of the earthquake. The basic construction is shown in figure 14. The reservoir, located on a bluff overlooking the Pacific Ocean, is about 540 feet above sea level. Upon discovering the leak, numerous homes were evacuated at the direction of the public authorities. This was done because the scope of the damage was not known,

Photo 29. Leak in east wall of reservoir shown in figure 14. *Photo by San Francisco Examiner.*

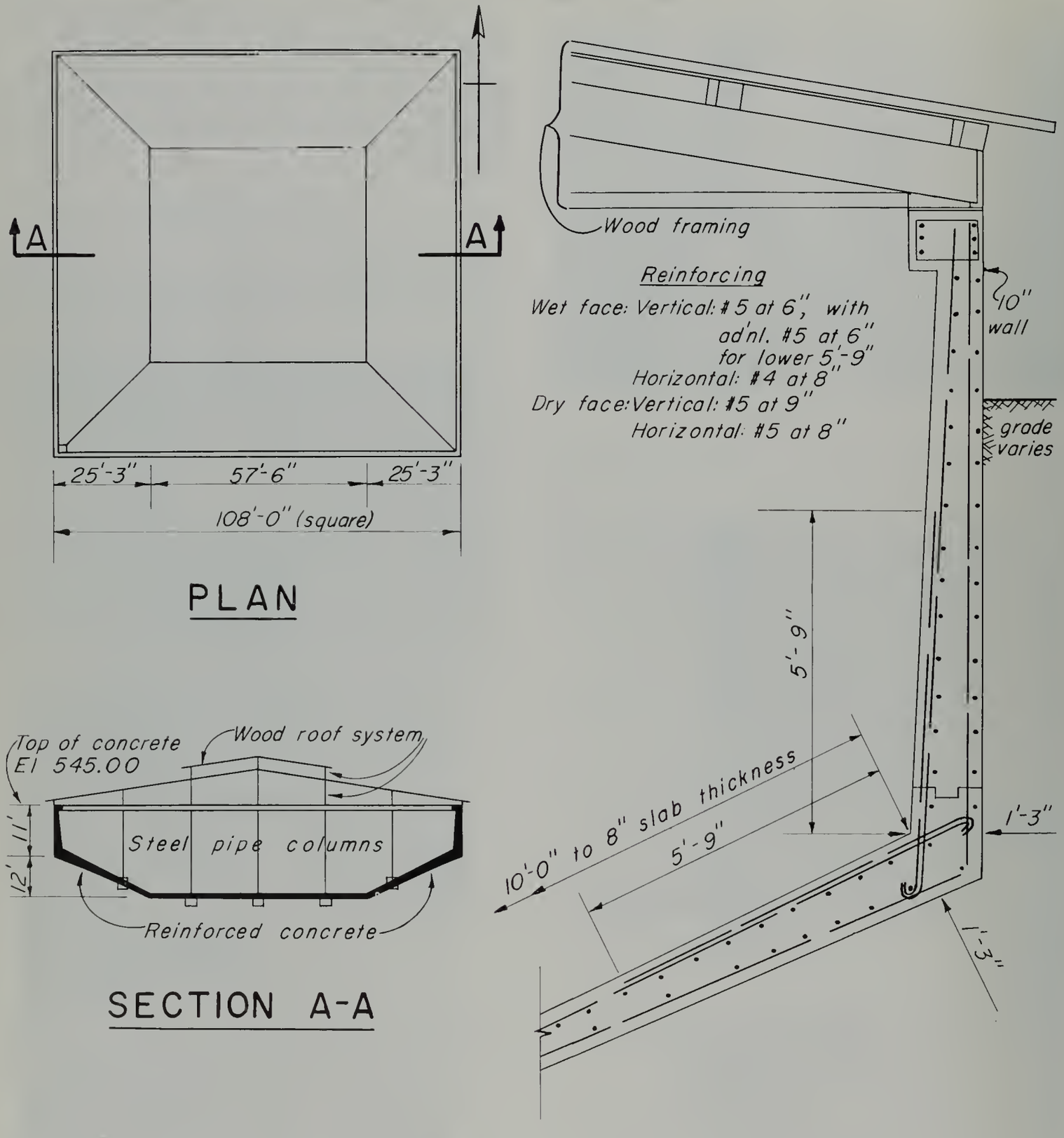


FIGURE 14. Plan, section, and detail of reservoir in Westlake Palisades, Daly City.

and there was a fear that aftershocks might cause complete failure.

The east wall of the reservoir cracked as shown in photo 29, releasing water. The length and size of the crack below the ground surface has not been determined at this writing, as the reservoir has been only partly dewatered. A preliminary examination suggests that the crack existed before the earthquake and extended above the ground surface at the time of the shock. This reasoning implies that some undetected leakage occurred prior to the earthquake.

The soil at this location is a loosely cemented sandstone, typical in the Westlake Palisades area. Backfill around the sides of the reservoir settled as shown in photo 30; the amount of settling, if any, at the time of the shock has not been determined.

Photo 30. Settlement around reservoir in Westlake Palisades (figure 14). Some settlement probably occurred prior to earthquake.

San Francisco. The following is based on a report prepared by the San Francisco Water Department, and is released with their permission.

The San Francisco distributing system had four leaks in steel mains, all of which appeared to be in corrosion-weakened pipes. Two leaks were in 30-inch mains, one in a 3-inch main, and one in a main for which the size was not specified. All of these leaks were in mains located in the southwestern part of the city, close to the more heavily shaken areas. Also, three air valve leaks indicated a surge of water in the large mains. Surging of water in pipelines, with the attendant damage to corrosion weakened pipes, has been noted in other earthquakes. This was extensively described in an unpublished report by the Los Angeles Department of Water and Power after the Kern County earthquake of July 21, 1952.

At the Lake Merced Pump Station in San Francisco, a filled area settled 4 to 6 inches, severing a 12-inch pipe from the station.

A total of a hundred-odd services were broken; these were mainly old galvanized services, but a few copper services pulled apart at the meters. These breaks were scattered throughout the city, although there was some concentration in the southwestern part of the city. The distribution reservoirs in San Francisco showed no structural damage, although some minor earthquake effects were noted.

Pressure recordings taken from the pipelines located on the San Francisco peninsula showed surges as straight lines on pressure charts, indicating that they were of short duration. These pressure variations should not be taken too literally, as the earthquake also shook the recording needles. For example, a similar recording device, registering temperature in an alum tank, showed instantaneous temperature variations; this of course was the result of vibration of the recording needle. Other factors that influenced the surge readings were the sensitivity of the recording instrument and the length of the tube from the line.

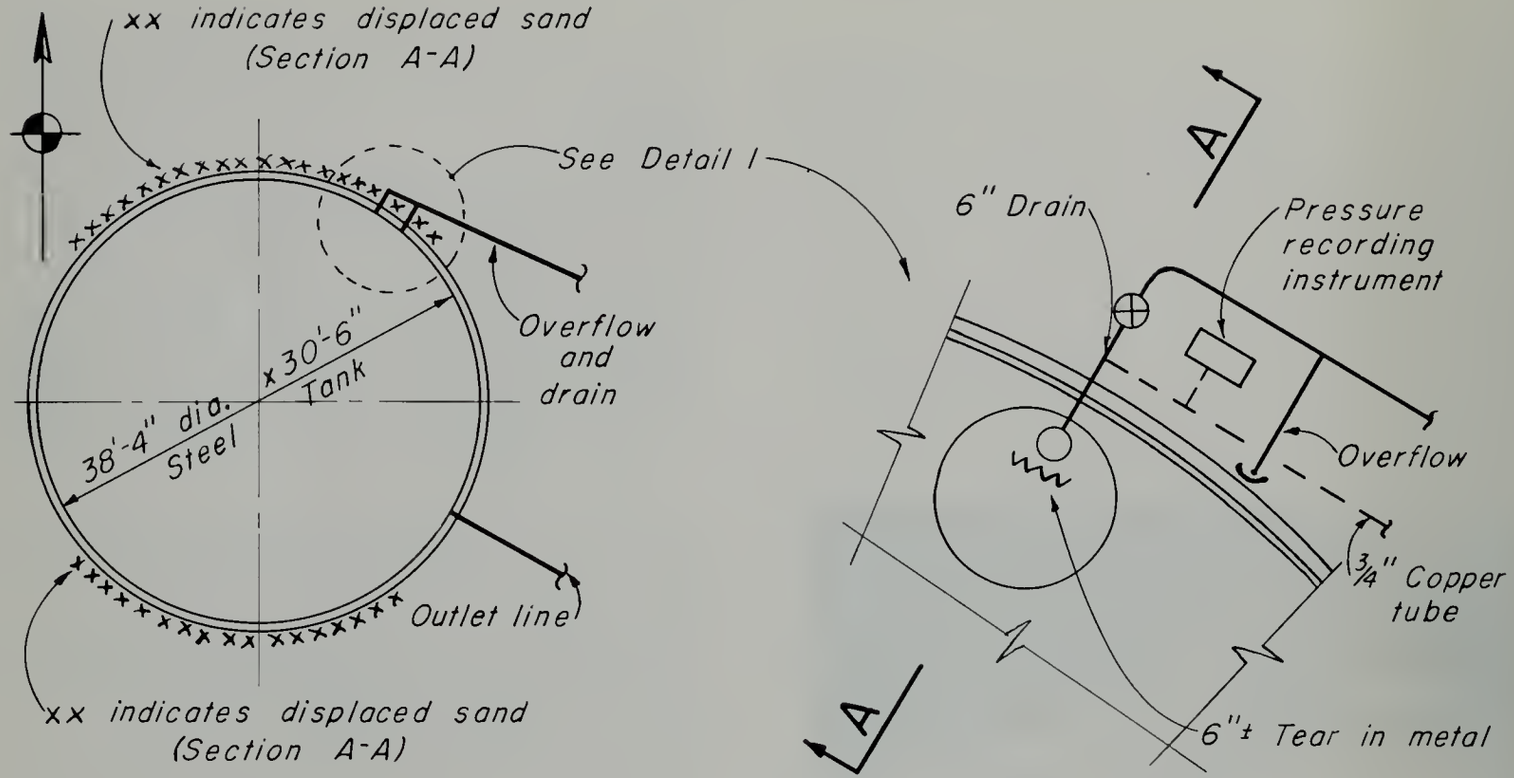
San Francisco Peninsula. California Water Service supplies water to a number of communities on the San Francisco peninsula. As with the other water systems, damage was light.

Damage to mains was restricted to breaks in one 6-inch cast-iron main and one 6-inch asbestos-cement pipe. Both were in the South San Francisco area. No particular significance was attached to the breaks.

An unknown number of household water pipe breaks occurred, but they were believed to be considerably less in number than in Daly City or San Francisco. It was also observed that this type of break would tend to be consistent within any housing tract, but would vary from tract to tract. It seems reasonable that this was the result of varying construction techniques instead of varying earthquake intensities.

The California Water Service has a number of steel ground level storage tanks, including the Winston Manor tank shown diagramatically in figure 15. Damage at this tank consisted of a break at a $\frac{3}{4}$-inch corporation cock connection, a break in the discharge line at a poorly connected elbow, and a tear in the $\frac{1}{4}$-inch sump plate. A

Photo 31. Displaced sand at Winston Manor tank. Photograph taken several hours after the shock. See figure 1 for tank location. *Photo by J. R. Rossum, California Water Service.*

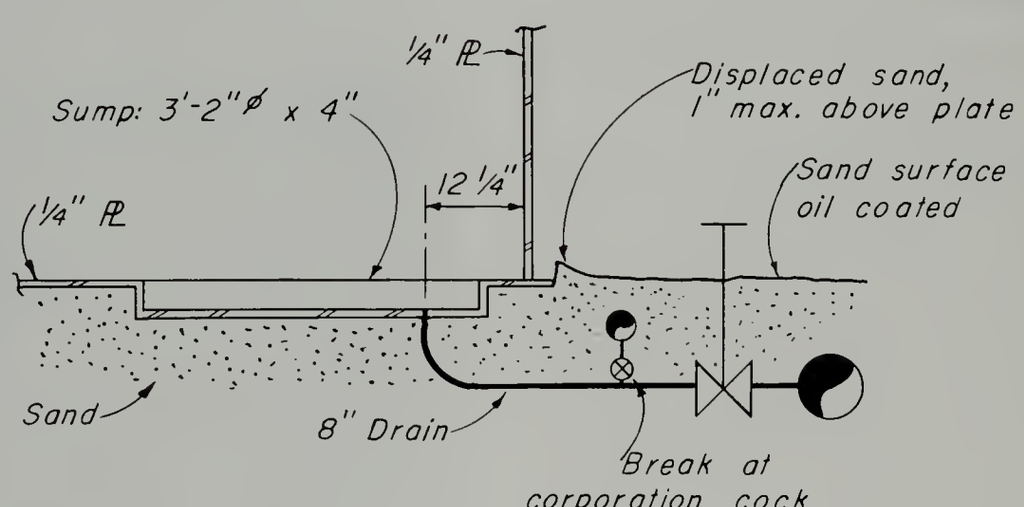


PLAN AT TANK BOTTOM

Diagrammatic

DETAIL I

Diagrammatic



SECTION A-A

FIGURE 15. Winston Manor tank, and effect of earthquake. For location of tank, see figure 1.

pressure recording instrument, used to measure water height in the tank, read as follows:

Steady state prior to shock:	29 feet
At the time of shock:	
Maximum:	33 feet
Minimum:	14.5 feet

Since the tank is only 30 feet 6 inches high, readings from this type of instrument are not too reliable. Displaced sand around the tank's rim was noted at the time of the shock, but was not investigated critically until July 23, 1957; it is possible that the depression usually found beneath the rim of the tank had been filled by intervening rains. Displaced sand was also noted at California Water Service's 500,000-gallon Brentwood tank. Again, no depression was found under the rim at the rather late inspection date.

Gas

Pacific Gas and Electric Company supplies gas throughout the San Francisco Bay area. Their gas facilities received very small damage as is indicated by the following information supplied by them:

"In San Francisco a cracked weld on the 26″ Transmission Main #109 near Alemany Boulevard was very likely caused by the quake. Two cast iron mains are known to have been broken. Over that week end 128 calls were received from customers reporting broken mains and services. In not all of these cases, however, did we find evidence of leaking gas.

"In Hayward, East Bay Division, only 1 case was reported; there was minor damage due to gas leaking from a broken house line.

"In Millsdale, San Jose Division, an overhead house line broke at couplings. Gas was turned off with no damage."

Gas shutoff valves of a type that are actuated by earthquake forces functioned at the three locations shown on figure 1.

Electric Power

The electric distribution system of the Pacific Gas and Electric Company suffered practically no damage. The company's observations of the earthquake effects are of interest, and the following is from information supplied by them.

"There were only three cases of overhead line conductor failures which possibly can be attributed to the earthquake. In each case, however, positive proof of the cause of failure is lacking.

"The greatest damage to overhead distribution facilities was the breakage of street light glassware. Practically all of the breakage was on upright type units either mounted on brackets on wood poles or on electroliers. Breakage directly attributable to the earthquake was distributed as follows:

San Francisco	88
Daly City	7
South San Francisco	4
San Bruno	2

"In San Francisco approximately 60% of the breakage occurred in the area west of Twin Peaks and south of Golden Gate Park. Breakage in the remainder of San Francisco and in other cities was scattered throughout the area.

"Minor damage resulted and service interruptions were experienced in a number of our substations in the San Francisco area and in a number of the buildings, additional cracks were noticed although no structural damage of consequence resulted."

Considering the value and extent of the Pacific Gas and Electric's properties, the foregoing effects may be considered more in the category of a nuisance.

Sewage Systems

No detailed survey has been made, but there were no known instances of damage to sewage-collecting systems.

Telephone

No damage to telephone equipment occurred. The dial telephone system was overloaded, and many calls could not be completed because of the very great increase in the number of calls. The system returned to normal as soon as the overload dropped. This type of overloading has been noted in other earthquakes.

FIRE PROTECTION

Daly City Fire Department. The Daly City Fire Department received 63 calls from street boxes, telephones, etc., from the time of occurrence of the shock until midnight of that day.

Table 3. Summary of calls to Daly City Fire Department

Date	Gas leak	Hazardous chimney	Sprinkler alarm	Fire	Other
March 22, 1957 11:44a.m.-12 p.m.	25	23	2	2	11
March 23, 1957	1	14	–	–	2

Gas leaks were in dwellings, and usually associated with overturned or shifted water heaters. A total of 44 damaged brick chimneys were pulled down by the fire department between March 22nd and March 26th, though undoubtedly many more were damaged or destroyed. Brick chimneys in the area are few, as many patent flues are used. No evaluation has been made of what is believed to have been relatively little damage to patent flues.

The following is quoted from a report prepared by the National Board of Fire Underwriters:

"Directly following the 11:44 a.m. shock, ten blasts were sounded on the air-horn; thirty-five minutes later, the disaster call was sounded to speed up response of volunteers and to call out the civil disaster personnel. By 12:30 p.m., most emergency personnel had reported and were dispatched to five pre-established control points. About 90 percent of the volunteers are reported to have responded. Fire department apparatus which had immediately been driven clear of stations, were assigned to some, police cars to others. Apparatus was not returned to quarters until 1:00 a.m., March 23. Radios were available at all control points initially, but as calls were received it was necessary for radio equipped units to leave, in some cases leaving fire department apparatus without communications. These units were later moved to where they could be reached by municipal controlled telephone system. At no time was there any malfunctioning of municipally controlled communications equipment.

"At about 3:00 p.m., an inspection program was started to include all of the some 8,500 homes in the Westlake area to check for leaking gas. Westlake is a portion of Daly City that has been built almost entirely since

1946, and is primarily of two-story detached homes. The area is still growing and houses are being built in considerable numbers. About 40 men from the fire, building and police departments were assigned and worked until 10:00 p.m. Friday, all day Saturday and concluding Sunday morning at inspecting of homes. Inspections were limited to a checking of gas burning devices and where there was evidence of units having been shifted by the earthquake, the gas was turned off and the occupant advised to get in touch with the local gas utility for the restoration of service. In one subdivision 353 services were shut off. While making inspections, fire apparatus was considered in service and able to respond to any fire calls. The only fire directly attributed to earthquake action was in a two-story apartment house and was caused by an overturned gas-fired water heater. The fire was readily extinguished by one man with a garden hose freeing the remainder of the crew for inspection work. The fire was reported by street box which are well distributed throughout the Westlake area."

San Francisco Fire Department. The following is is quoted from a report prepared by the National Board of Fire Underwriters:

"No fires within the city are believed to have been directly caused by the earthquakes. A third-alarm fire occurring at 3:58 p.m. on March 22 in a warehouse has been attributed to juveniles.

"The fire alarm operations were unaffected except for an apparent inability for phone calls to be received when originating east of Fillmore Street. An attempt to reach the local gas utility from alarm headquarters by telephone took 45 minutes. From west of Fillmore, phone calls were received at an average of one every two minutes for the first two hours, then at a diminishing frequency. Until the emergency warning call was tapped out at 9:03 p.m. on March 22, 117 alarms were received, 97 by telephone and 20 by box. Causes are as given below. Data are from the San Francisco Fire Department's daily fire record.

Daily Fire Record

Item	*Cause of alarm*	*Number*
1.	Broken water line	5
2.	Damaged chimney	39
3.	Damaged cornice	4
4.	Broken window	7
5.	Water flow alarm	2
6.	Gas leak	14
7.	Fallen wires	3
8.	Emergency 10-1	1
9.	Miscellaneous fire calls *	30
10.	False alarms	12
	Total	117

* Includes 2d and 3d alarms.

"Alarm system, radio and voice circuit operation were unaffected. Two additional operators were on duty at the alarm office—one by assignment and one volunteer.

"Response to alarms was as designated by running cards; no limited response was ordered. At no time until the third alarm fire was more than ten per cent of the apparatus in service out of quarters. The off-shift was not called although a few reported voluntarily."

A survey conducted by San Francisco Fire Department personnel showed that some 23 fire stations out of a total of 50 had cracked plaster, and also broken windows in a few instances. None of the damage was considered structural. The cracking occurred to earthquake-resistant stations (new as well as reconstructed) and also to nonearthquake-resistant stations.

San Francisco has a high-pressure water system, separate from the domestic water system, for fire fighting use. It services the northeastern part of the city and furnishes protection to about 14 square miles of congested high-value districts. No damage was reported to this system or to the cisterns connected with this system.

Sprinkler Systems. The following information is summarized from a privately printed report, published by the Sprinklered Risk Department of the Pacific Fire Rating Bureau. This has been supplemented from other sources.

The most seriously damaged sprinkler piping was in an old two-story wood frame building located on filled ground near the Islais Creek area of San Francisco. Actual damage was the cracking of the feed main on the second story where it rises and passes through the second floor. The sprinkler equipment did not conform to accepted earthquake-resistant construction practices.

One pipe leak was reported in South San Francisco. Numerous instances of pipes shifting in their supports were noted.

At the San Francisco Airport, one automatic sprinkler head in each of Buildings 13 and 15 at the United Air Lines maintenance base was opened from contact with a vibrating structural X-bracing member in the plane of the roof trusses. Also, at United Air Lines Base Building 15, a 1-inch sprinkler pipe extension through an 8-inch hollow concrete block wall was broken off at a cast-iron fitting. Sprinkler piping, even if well braced, can perform only little better than the building. See photo 24 for damaged pipe supports at a structural separation in a building.

PHOTO 32. Sprinkler head (right center) broke when rod from X-bracing vibrated. Looking up at roof from floor. Burlingame, California.

No trouble was reported from any pressure tank.

As far as is known, all tanks in San Francisco which had an automatic alarm system sent in signals. These signals are sent in when the water within the tank goes through a double amplitude of 6 inches. There are an estimated 150 locations having one or more tanks with alarms. Four from Oakland sent in alarms.

EFFECT OF THE MARCH 22, 1957 EARTHQUAKE ON PUBLIC SCHOOLS

By Manley W. Sahlberg
Principal Structural Engineer
California State Division of Architecture

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ABSTRACT

The San Francisco earthquake of March 22, 1957 revealed several weaknesses in school construction, mostly nonstructural and minor in nature. None of the schools constructed under the controls of the State Field Act, which became law in 1933, suffered any structural damage, and only a few sustained nonstructural damage.

Most San Francisco schools built since 1923 are two-story structures of reinforced concrete, or of reinforced concrete with a structural steel frame. Such structures have great inherent strength to resist lateral forces, which accounts for the relatively small amount of damage inflicted on San Francisco schools by this earthquake.

Appreciable damage of varying degree was noted in the epicentral area from the center of San Francisco to Millbrae, San Mateo County, 14 miles south on the peninsula.

Schools of Marin County, north of the Golden Gate, and those schools across San Francisco Bay in Alameda and Contra Costa Counties, suffered negligible damage.

INTRODUCTION

The California State Division of Architecture has the responsibility of administering the "Field Act," a law enacted by the State Legislature immediately following the disastrous Long Beach earthquake in 1933. This Act vests in the Division of Architecture the responsibility to attain the requisite structural stability of public school buildings to withstand vertical loads and lateral forces, and to insure safety of construction. The "Field Act," together with the rules and regulations established by the Division of Architecture to effectually guide construction of public schools, is now included in Title 21 of the California Administrative Code. The law is not retroactive and, therefore, school buildings may be classified as being either *approved* or *unapproved*. All public school construction since the law's enactment has been checked and approved by the Division, as have the buildings that have undergone structural rehabilitation during the intervening time.

In the area in and around San Francisco where the March 1957 earthquake was noticeable, there are a great many school structures. Most of the schools have several buildings. In the older schools there are both approved and unapproved buildings, as well as some buildings that have been rehabilitated according to code requirements.

A part of the job of the Schoolhouse Section of the State Division of Architecture is to evaluate the effect of earthquakes on public school buildings. When the San Francisco earthquake occurred, swaying of the heavy fluorescent light fixtures was observed in the principal engineer's office, followed by one fixture falling to the floor with an explosion-like noise (photo 1). Failure was later found to be due to a substitution of friction-type nuts on the hangers instead of the threaded type specified at the time of installation. This event, and jamming of the phone system, delayed the Division's investigation momentarily, but contact was established with the seismological station of the University of California, through radio. There it was learned that the earthquake centered in the Daly City-Westlake region, and was probably the result of movement on the San Andreas fault. The newscasts stated that only very minor and negligible damage should be expected outside a 15-mile radius of Daly City. This information allowed concentration of damage examination within the area nearest the epicenter.

In the following paragraphs, numerals following school names indicate location of schools on the area map shown in figure 1 of the preceding paper by Steinbrugge, Bush, and Zacher.

SAN FRANCISCO SCHOOLS

In San Francisco there are more than 125 school sites or school plants. Appreciable damage was reported on or found in only 11 schools west of a line formed by Castro and Divisadero Streets.

Lowell High School (1) was rehabilitated in 1935. It is a three-story building of steel framing and brick masonry walls. The floor and roof construction is of wood. The studs of the interior partitions are also of wood, and most of the ceilings and walls are plaster on wood lath.

PHOTO 1. Fallen lighting fixture in office of Principal Structural Engineer, State Division of Architecture, in San Francisco.

Plaster fell in sizeable chunks from ceilings in many classrooms, in the library, the chemistry laboratory, and the auditorium. Horizontal cracks occurred in the stairwells at floor levels. Plastered interior walls, throughout the building, developed numerous cracks.

Andrew Jackson Elementary School (2), two blocks from Lowell High School, is a two-story reinforced concrete building constructed in 1924. It developed some cracks in the marble facing at the entrance.

James Lick Junior School (3), a three-story reinforced concrete structure built in 1932, suffered only a few plaster cracks. Two weeks before the earthquake, the school department's maintenance crews had removed the stone facing of the parapets which, it had been discovered, were in a loosened condition.

Geary Elementary School (4), constructed in 1930, is another two-story reinforced concrete structure. It suffered no damage.

Presidio Junior High School (5), constructed in 1929, is a three-story structure of steel frame and reinforced concrete. Large pieces of unanchored cast stone ornamentation, at the top of a chimney rising about 35 feet above the roof, loosened and fell (see photo 2). One piece, about 350 pounds, plunged through a skylight and smashed into a toilet room on the third floor, crumpling the metal partitions (see photo 3). Another piece made a large indentation in the courtyard below, after hitting the roof and crushing several roof tiles. The walls of the stairwell had diagonal shear cracks. The structure, as a whole, reacted very well to the forces imposed by the earthquake.

George Washington High School (6) was constructed in 1936. It is a three-story reinforced concrete structure with large windows. Except for minor plaster cracks there was no appreciable damage to this school.

Photo 2. Stack of Presidio Junior High School in San Francisco from which heavy ornamentation fell. *Photo by San Francisco Chronicle.*

Photo 3. Smashed toilet partition caused by ornamental masonry block falling from top of stack of Presidio Junior High School in San Francisco. *Photo by San Francisco Chronicle.*

West Portal Elementary School (7), a two-story reinforced concrete structure, was built in 1927, and some work was done on it in 1932. This school appears to be settling toward Twin Peaks Tunnel which lies below. The school building did not show any new cracks but the old ones "worked" somewhat.

Noriega Elementary School (8) was constructed in 1951. Here, only a lighting fixture fell to the floor.

City College of San Francisco (9) had some ceramic tile facing fall from the northeast corner of the Science Building, a structure built in 1940. The tile fastening depends on cement mortar adhesion. No other damage was reported or noticed.

Sheridan Elementary School (10), an unapproved structure, is a three-story wood frame building, constructed in 1909. The 14-foot brick chimney crumpled and fell apart near the west escape stairs.

Frederick Burk Elementary School (11) was constructed in 1955. It developed only minor cracks.

SAN MATEO COUNTY SCHOOLS

In the area north of Burlingame in San Mateo County, there are more than 33 school plants, many of which have several buildings, especially the high schools. Appreciable minor damage of interest occurred in only 11 of these plants.

Thorton Elementary School (12) in Daly City, is an unapproved structure. Patches of plaster fell from wood lath.

Garden Village School (13) in Colma near Daly City, is an approved structure. Six glass panes were broken in the east-west walls of the north wing. There was also some slight cracking of the exterior stucco plaster.

Olympia School (14) in Daly City, is a one-story structure with reinforced concrete lift slab roof supported on reinforced concrete masonry walls. There was no damage except for slight nonstructural plaster cracking.

Jefferson Union High School (15), in Daly City, has various buildings. The main building is an unapproved structure. Patches of plaster were shaken from the wood-lath ceilings, light fixtures were thrown down, and cracks were opened in the plastered walls. A brick chimney was cracked.

The gymnasium and swimming pool buildings are approved structures. The rod bracing system was under stress and showed signs of marked movement. Some rods were loosened and the ridge strut was bowed out of line. Some roof tiles appeared to have shifted.

The cafeteria building is an approved building and showed signs of movement and deflection. A few small cracks developed in the plastered interior walls.

The shop building and the grandstand, both approved structures, experienced no damage.

Westmoor High School (16), all of its buildings approved, was under construction and nearing completion at the time of the earthquake. This school is located at the top of compacted sand hills in Westlake, very close

to the San Andreas fault. A shear connection failed in the shop building. This was caused by a large cluster of electrical conduits located in the concrete next to the connection, reducing the shear area and reducing the strength to transmit shear from lateral forces. Adjacent concrete columns, also transmitting lateral forces, were spalled slightly near the connection. In the gym building some reinforced grouted brick masonry was damaged because the structure was incomplete and still under construction.

SOUTH SAN FRANCISCO SCHOOLS

South San Francisco High School (17) is an approved structure. It had about 12 panes of glass broken. Storage batteries used for emergency power supply were dislodged from a shelf and were shorted out.

Buri-Buri Elementary School (18). Two clocks were thrown off the walls of this approved structure. Five panes of glass were broken in the long east and west walls, and two panes were broken in the short north and south walls.

Avalon Elementary School (19), an approved structure, suffered two broken panes of glass and minor plaster cracking.

SAN BRUNO PARK SCHOOL DISTRICT

Edgemont Elementary School (20) is an approved structure. Eight small panes of plate glass were cracked. There was also some slight plaster cracking.

Parkside Elementary School (21) is made up of several approved one-story structures of precast reinforced concrete, tilt-up walls. Movements occurred in the joints between many units and cracks were developed in the pointing-up material. In the auditorium building, the proscenium wall is made of plaster on wood studs and was not designed to resist lateral shears. This wall is tightly connected to the structure so that when the structure deflected the plaster cracked near the proscenium opening.

Capuchino High School (22) has many approved and interconnected buildings, most of which are two-story and are constructed of reinforced concrete. The school is located on a hillside. Twenty or more panes of glass were broken during the earthquake shocks, but other damage due to flexure was minor.

MILLBRAE AREA SCHOOLS

Green Hills Elementary School (23) is an approved plant. Here one complete sash, which was not properly anchored, fell.

Highland Elementary School (24). One loosened 6-inch-square fibre ceiling tile, attached by adhesives, fell and struck a child, but did not injure him.

Taylor Boulevard Elementary School (25) is an approved structure that was built in 1938. There was no damage, except that a full row of acoustical ceiling tile fell in the area of the auditorium stage (see photo 4). The ceiling framing is suspended adequately but the individual tiles depend on support from splines which rest on the runner members. Each of these tiles is 18 by 26 inches, weighs about 8 pounds, and consists of wood fibers covered with portland cement pressed into

PHOTO 4. Ceiling tiles dropped on stage of Auditorium of Taylor Boulevard School in Millbrae.

sheets about one inch thick. The ceiling has since been repaired by suspending each piece of tile at the corners by wires hung from the structural ceiling system, rather than relying on the spline system for support.

ALAMEDA AND CONTRA COSTA COUNTY SCHOOLS

Although the earthquake was distinctly felt in Oakland, San Leandro, Berkeley, Richmond, Lafayette, Martinez, Walnut Creek, and other nearby communities, the damage to school structures was reported as negligible. There are more than 82 public school plants in Oakland, and more than 23 schools in Berkeley.

MARIN COUNTY SCHOOLS

In Marin County there are more than 70 public school plants of various sizes. In only one school, the Central Elementary School, an approved rehabilitated structure located in Sausalito, was there noticeable minor damage —some new plaster cracking and some movement in several old shrinkage cracks in the concrete walls.

CONCLUSIONS

Although the San Francisco earthquake of March 22, 1957, was of moderate intensity, the damage it caused to school structures emphasizes the following important weaknesses:

(1) Plastering on wood lath, even in rehabilitated structures, is very vulnerable, and it may be expected that parts will fall from ceilings during moderate shocks.

(2) Unreinforced masonry, such as chimneys with weak mortar joints, is very dangerous.

(3) Cast stone and similar masonry ornamentation is particularly dangerous unless positively anchored to the structure.

(4) Glass breakage may be considerable, even in approved structures of reinforced masonry construction, unless deflection is provided for in the putty joints of the glass.

(5) Tile and masonry facings on buildings are dangerous unless positively anchored. The dependability of cement mortar adhesion has not been demonstrated. When adhesives are used alone, the workmanship, materials, and application methods must be seriously considered.

(6) There is too much slack in the joints of ceiling systems made up of unit tiles supported by splines. Tightness of the system around the periphery is insufficient in itself. Positive suspension of each unit of tile is necessary.

That no one was injured by falling objects, in or near the school structures subjected to this earthquake, is little short of miraculous. There were many places where serious injury might have occurred.

The San Francisco earthquake of March 22, 1957, caused no structural damage to any school building constructed under Field Act requirements. While it is understood that the earthquake was of moderate intensity, many structures near the epicenter had zero damage, even in their nonstructural, most fragile parts.

RESPONSE SPECTRUM ANALYSIS OF THE SAN FRANCISCO EARTHQUAKE OF MARCH 22, 1957

By D. E. Hudson and G. W. Housner
Division of Engineering
California Institute of Technology

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ABSTRACT

Strong-motion accelerometer records were obtained from five stations located in buildings in San Francisco and Oakland. Such a group of strong-motion records from a number of stations located within a relatively small area is a most important addition to our basic information on structural effects of earthquakes.

Ground motion in the March 1957 earthquake was somewhat different from most recorded strong-motion earthquakes, in that the time durations were relatively short and peak accelerations were large for a shock of this magnitude.

Spectrum curves indicate that the influence of damping in reducing the peak values was not as marked in this earthquake as in more typical damaging earthquakes. This is a consequence of the short duration of the earthquake and the fact that the maximum structural responses occurred near the start of the motion.

ACKNOWLEDGEMENTS

We should like to thank William K. Cloud, Chief of the Seismological Field Survey of the United States Coast and Geodetic Snrvey, for providing us with copies of the strong motion records, Professors Perry Byerly and Don Tocher of the Seismographic Station of the University of California, Berkeley, for information as to the location of the earthquake epicenter, and B. M. Basavaraj for assistance with the computations.

ANALYSIS OF THE RECORDS

The strong-motion accelerometer records from the San Francisco earthquake of 22 March 1957 are of particular interest for the study of the effects of earthquakes on structures for several reasons:

(1) For the first time a group of strong-motion records has been obtained for the same earthquake from a number of stations located within a relatively small area. A study of the effects of local geology on the distribution of relatively strong ground motions thus becomes possible.

(2) Complete records were obtained simultaneously of ground motion and of the structural motions at two different floors of a relatively tall building. The dynamic characteristics of this building are known from previous tests; thus an overall check of structural dynamics theories can be obtained under actual earthquake excitation.

(3) Although the earthquake was not a large one, the epicenter was sufficiently close to a downtown area so that significant magnitudes of structural acceleration were caused. An analysis of these structural accelerations should throw additional light on the adequacy of existing lateral-force codes.

(4) The ground motion was of a somewhat unusual character in that it had large accelerations but a short time duration. Since the influence of certain dynamic properties of structures may depend upon both the

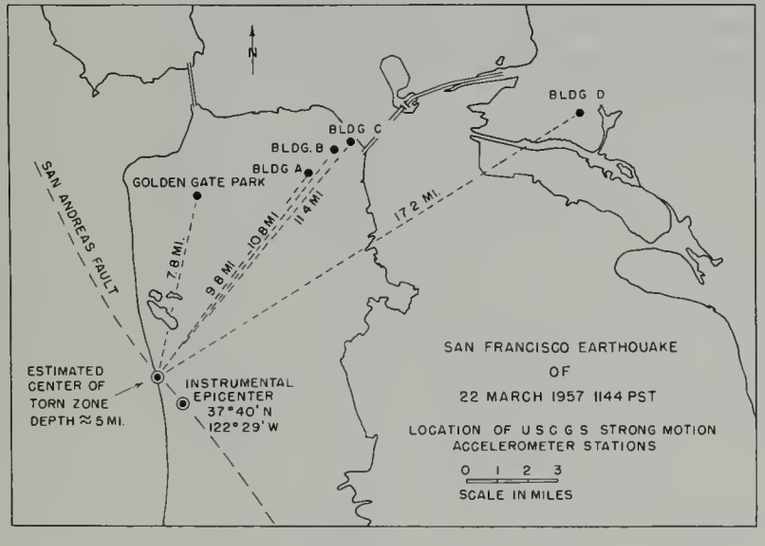
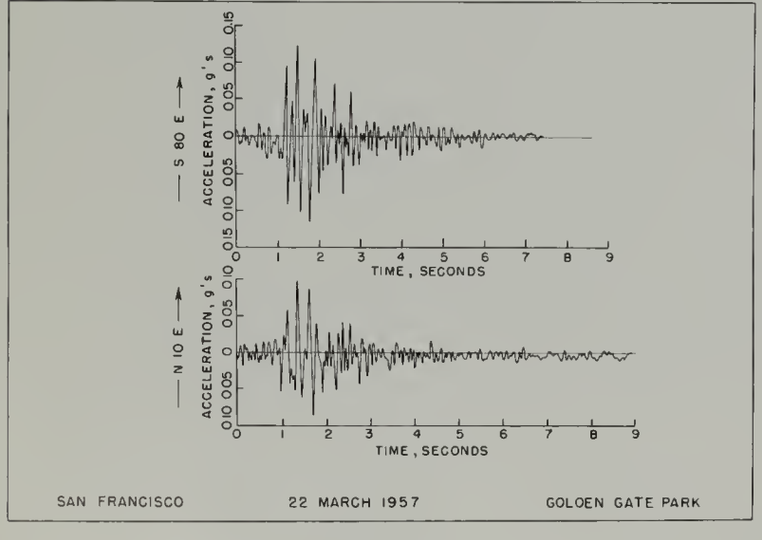


FIGURE 1.



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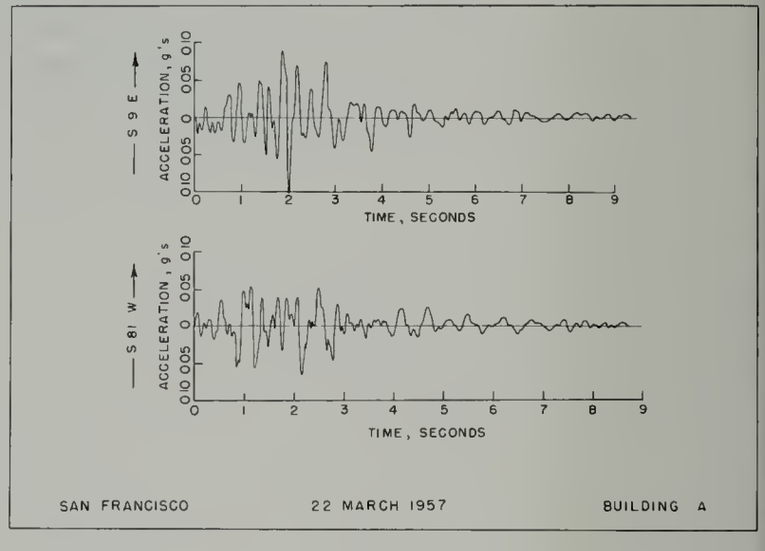

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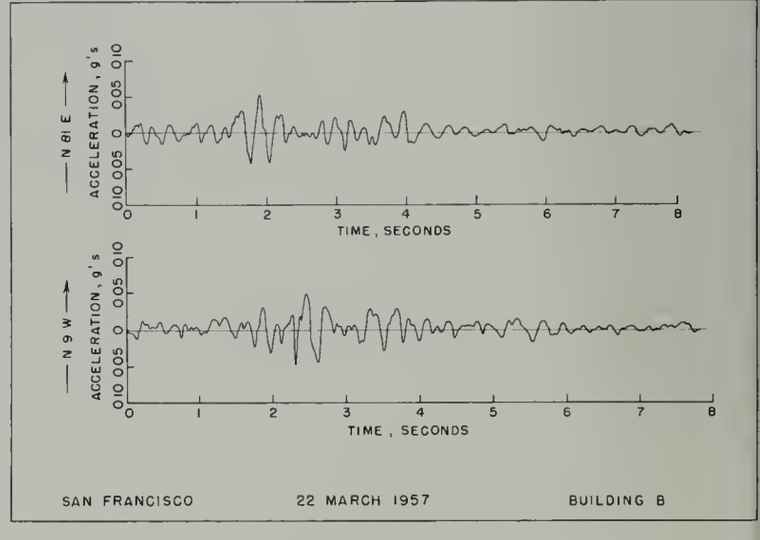

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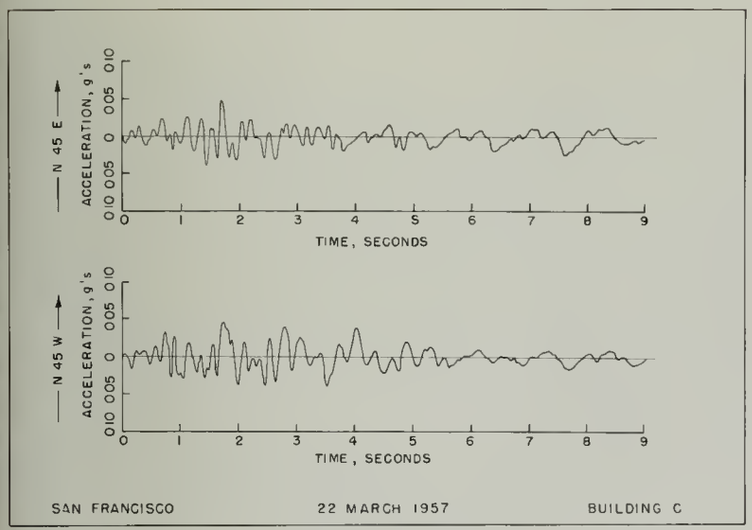

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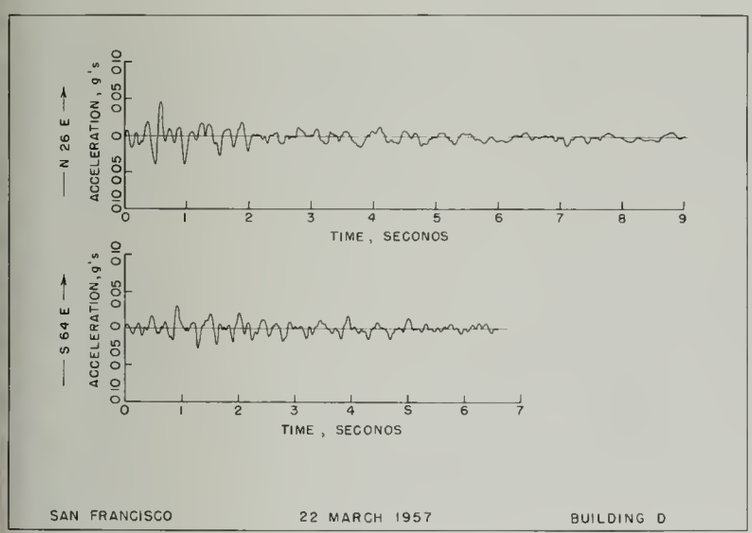

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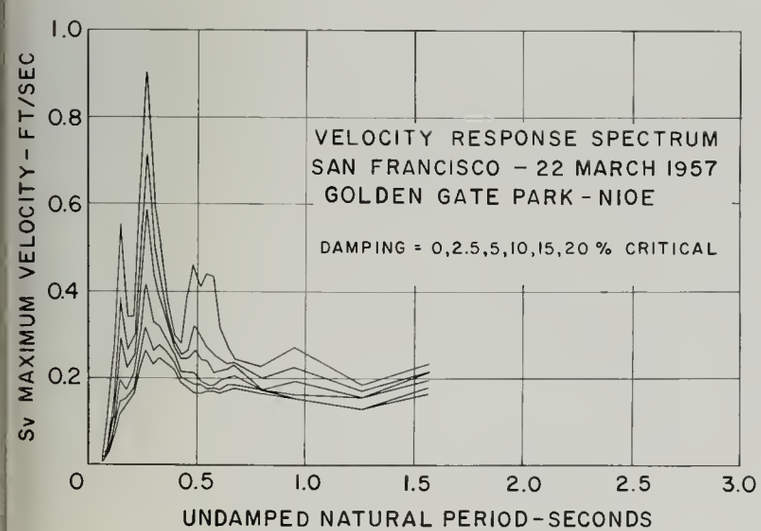

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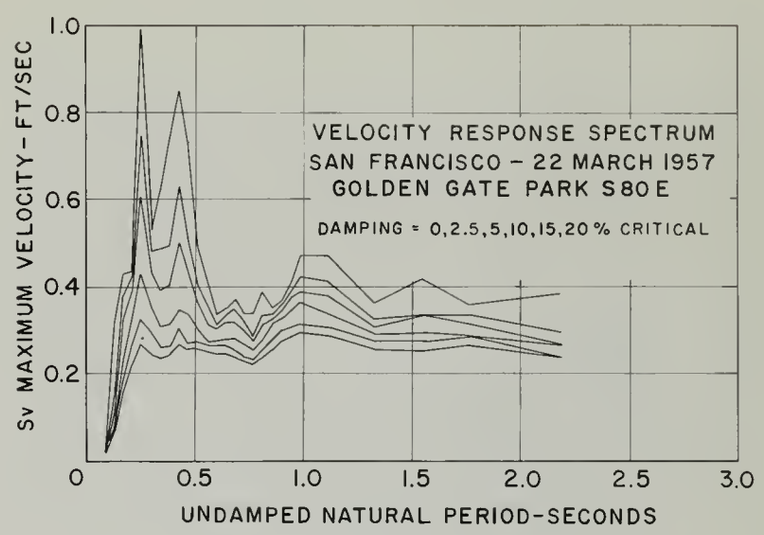

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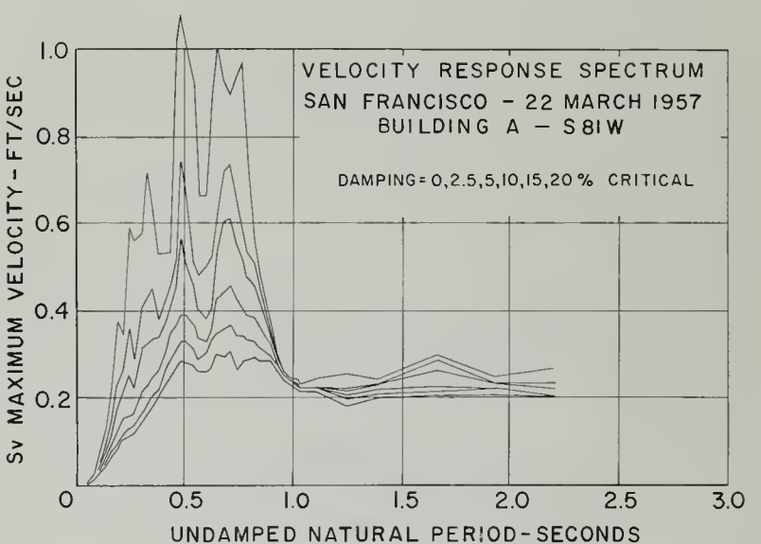

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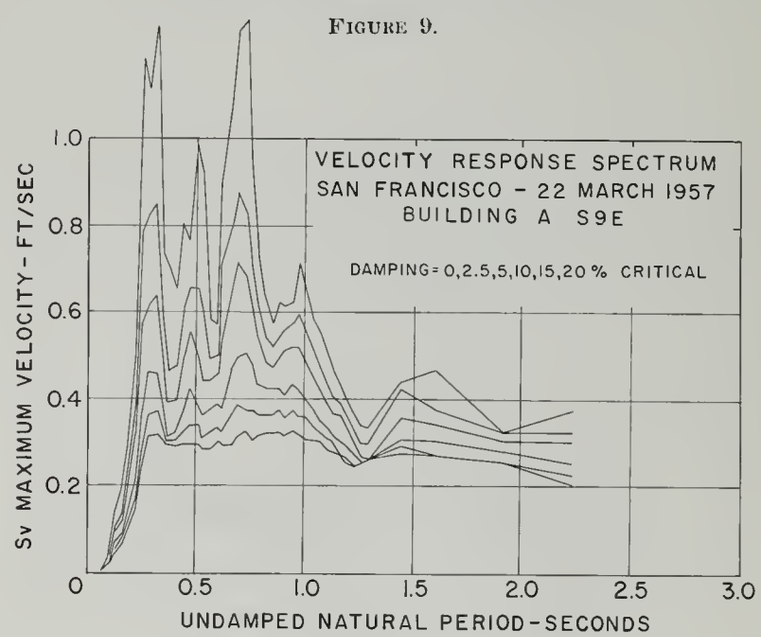

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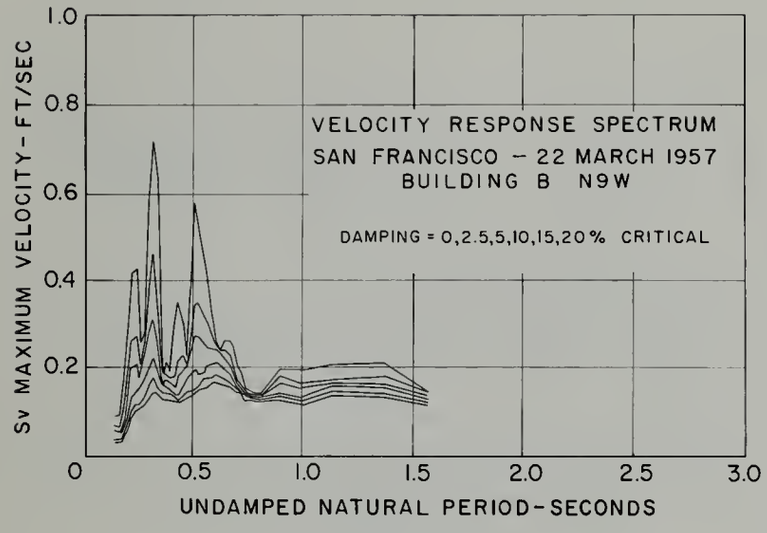

VELOCITY RESPONSE SPECTRUM
SAN FRANCISCO – 22 MARCH 1957
BUILDING B N9W
DAMPING = 0, 2.5, 5, 10, 15, 20% CRITICAL
Sv MAXIMUM VELOCITY – FT/SEC
UNDAMPED NATURAL PERIOD – SECONDS

FIGURE 11.

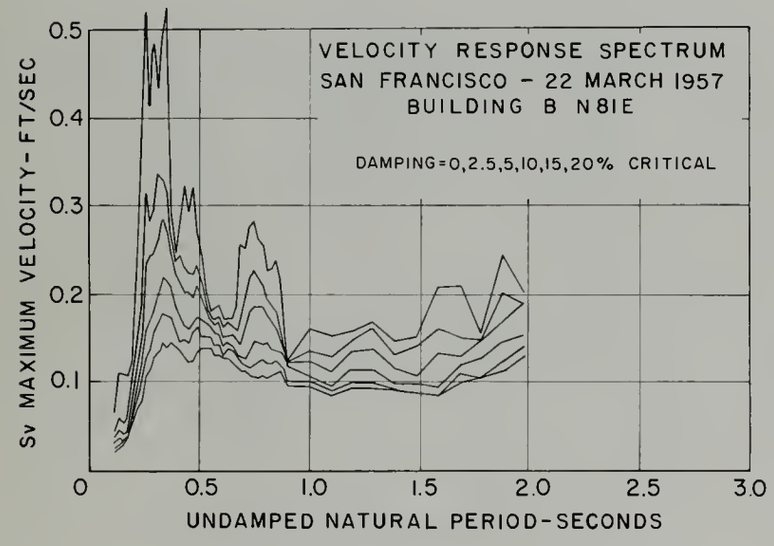
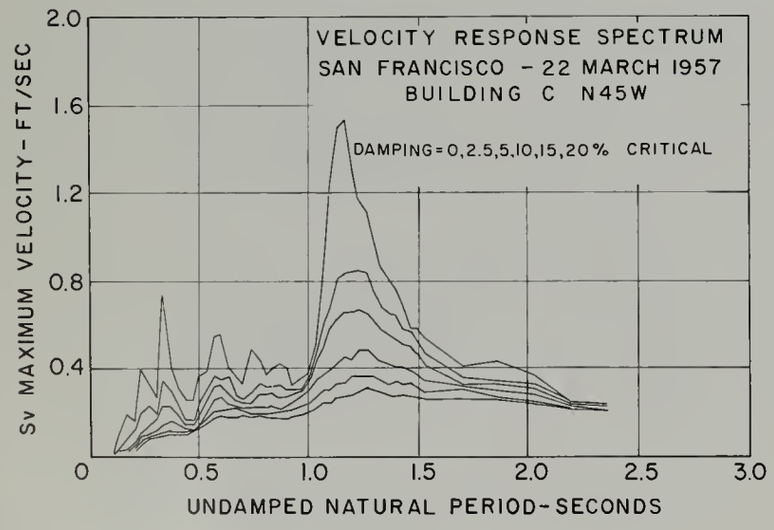

VELOCITY RESPONSE SPECTRUM
SAN FRANCISCO – 22 MARCH 1957
BUILDING B N81E
DAMPING = 0, 2.5, 5, 10, 15, 20% CRITICAL
Sv MAXIMUM VELOCITY – FT/SEC
UNDAMPED NATURAL PERIOD – SECONDS

FIGURE 12.


VELOCITY RESPONSE SPECTRUM
SAN FRANCISCO – 22 MARCH 1957
BUILDING C N45W
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Sv MAXIMUM VELOCITY – FT/SEC
UNDAMPED NATURAL PERIOD – SECONDS

FIGURE 13.

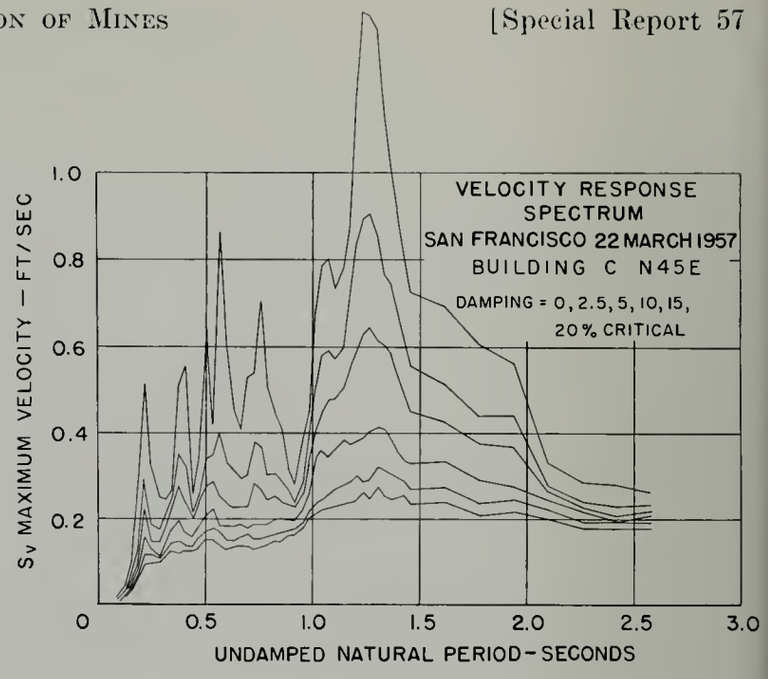
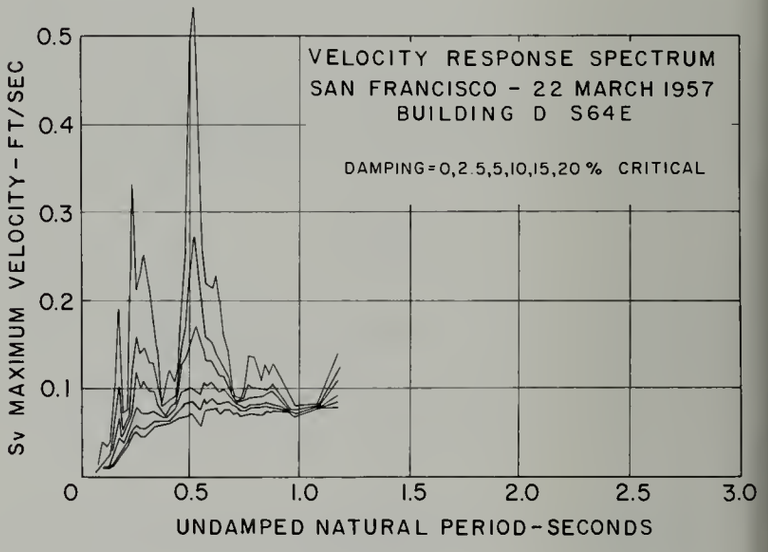

VELOCITY RESPONSE SPECTRUM
SAN FRANCISCO 22 MARCH 1957
BUILDING C N45E
DAMPING = 0, 2.5, 5, 10, 15, 20% CRITICAL
Sv MAXIMUM VELOCITY – FT/SEC
UNDAMPED NATURAL PERIOD – SECONDS

FIGURE 14.


VELOCITY RESPONSE SPECTRUM
SAN FRANCISCO – 22 MARCH 1957
BUILDING D S64E
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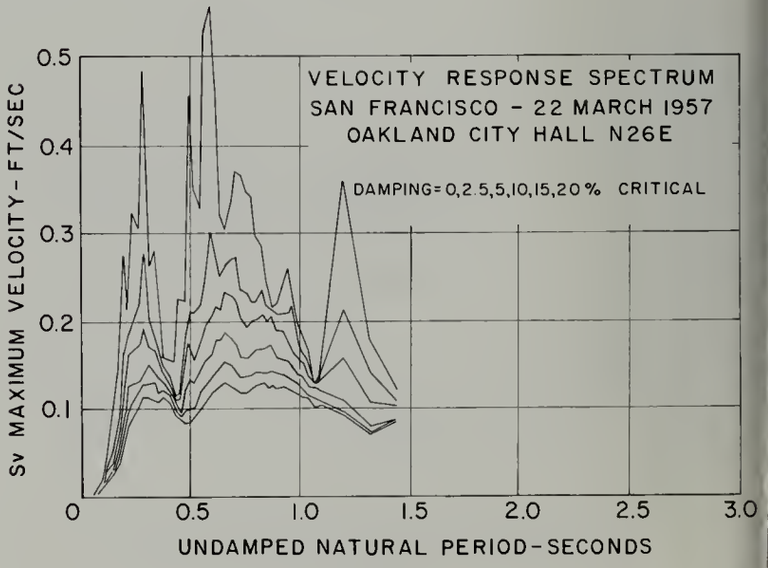
Sv MAXIMUM VELOCITY – FT/SEC
UNDAMPED NATURAL PERIOD – SECONDS

FIGURE 15.


VELOCITY RESPONSE SPECTRUM
SAN FRANCISCO – 22 MARCH 1957
OAKLAND CITY HALL N26E
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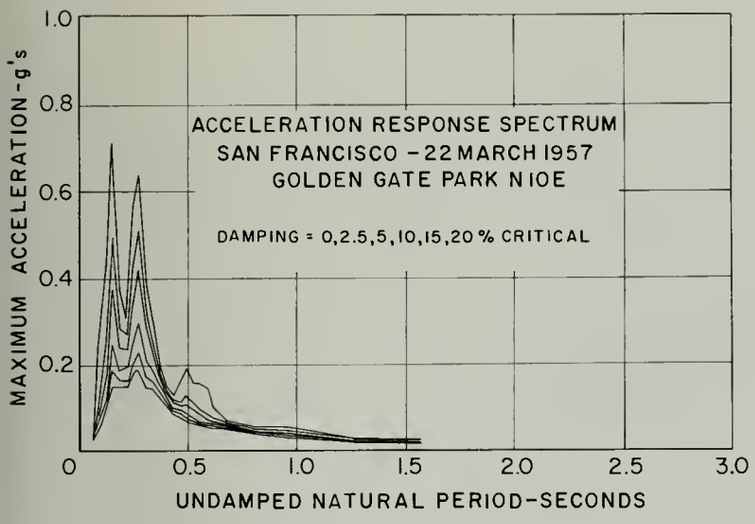
Sv MAXIMUM VELOCITY – FT/SEC
UNDAMPED NATURAL PERIOD – SECONDS

FIGURE 16.


ACCELERATION RESPONSE SPECTRUM
SAN FRANCISCO - 22 MARCH 1957
GOLDEN GATE PARK N10E
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MAXIMUM ACCELERATION-g's
UNDAMPED NATURAL PERIOD-SECONDS

Figure 17.

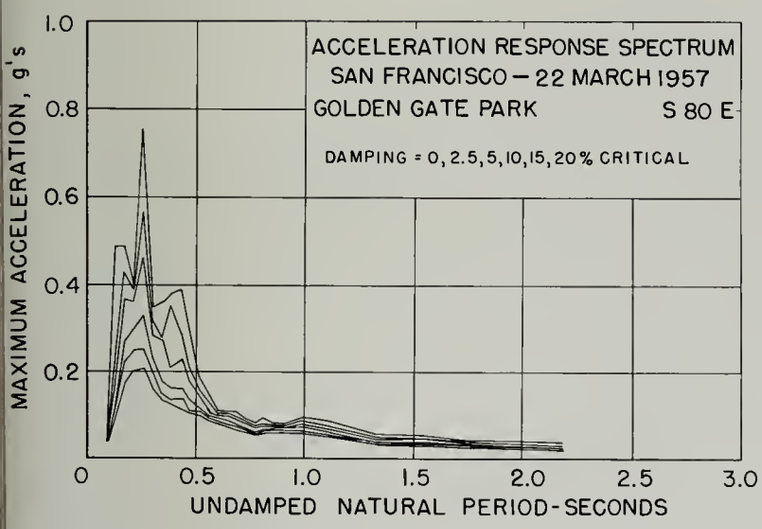
ACCELERATION RESPONSE SPECTRUM
SAN FRANCISCO - 22 MARCH 1957
GOLDEN GATE PARK S 80 E
DAMPING = 0, 2.5, 5, 10, 15, 20 % CRITICAL
MAXIMUM ACCELERATION, g's
UNDAMPED NATURAL PERIOD-SECONDS

Figure 18.

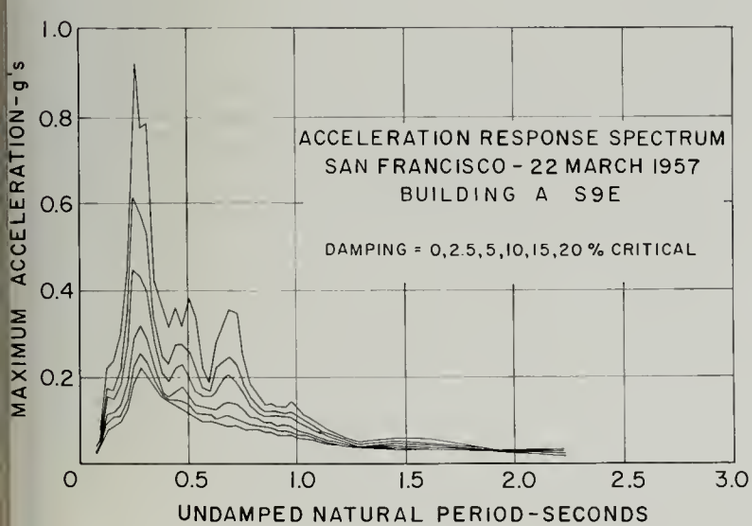
ACCELERATION RESPONSE SPECTRUM
SAN FRANCISCO - 22 MARCH 1957
BUILDING A S9E
DAMPING = 0, 2.5, 5, 10, 15, 20 % CRITICAL
MAXIMUM ACCELERATION-g's
UNDAMPED NATURAL PERIOD-SECONDS

Figure 19.

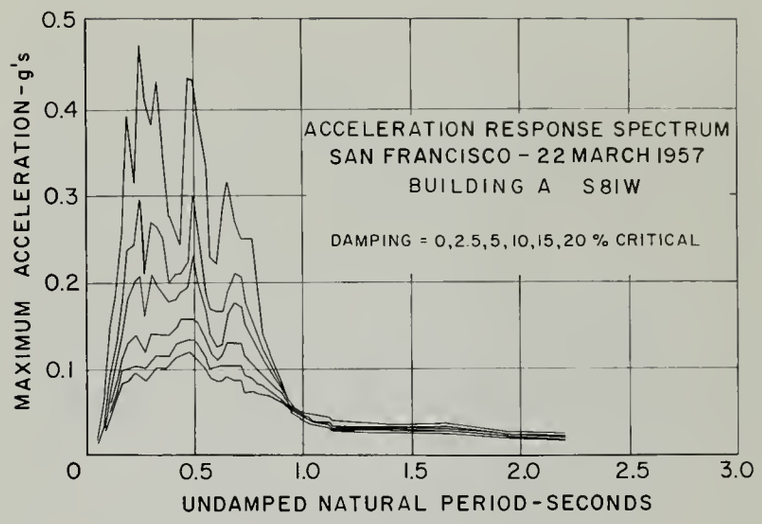
ACCELERATION RESPONSE SPECTRUM
SAN FRANCISCO - 22 MARCH 1957
BUILDING A S81W
DAMPING = 0, 2.5, 5, 10, 15, 20 % CRITICAL
MAXIMUM ACCELERATION-g's
UNDAMPED NATURAL PERIOD-SECONDS

Figure 20.

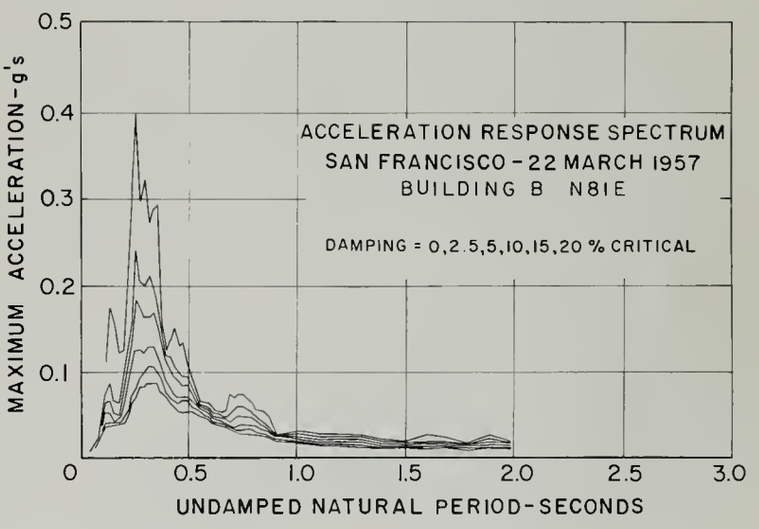
ACCELERATION RESPONSE SPECTRUM
SAN FRANCISCO - 22 MARCH 1957
BUILDING B N81E
DAMPING = 0, 2.5, 5, 10, 15, 20 % CRITICAL
MAXIMUM ACCELERATION-g's
UNDAMPED NATURAL PERIOD-SECONDS

Figure 21.

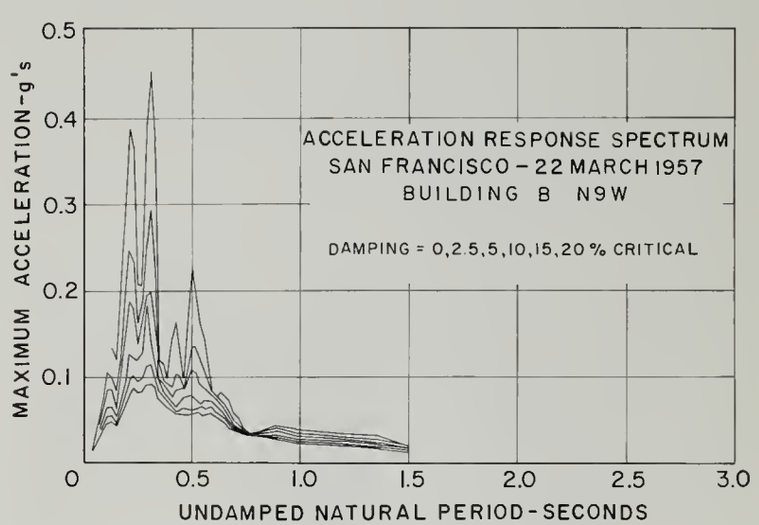
ACCELERATION RESPONSE SPECTRUM
SAN FRANCISCO - 22 MARCH 1957
BUILDING B N9W
DAMPING = 0, 2.5, 5, 10, 15, 20 % CRITICAL
MAXIMUM ACCELERATION-g's
UNDAMPED NATURAL PERIOD-SECONDS

Figure 22.

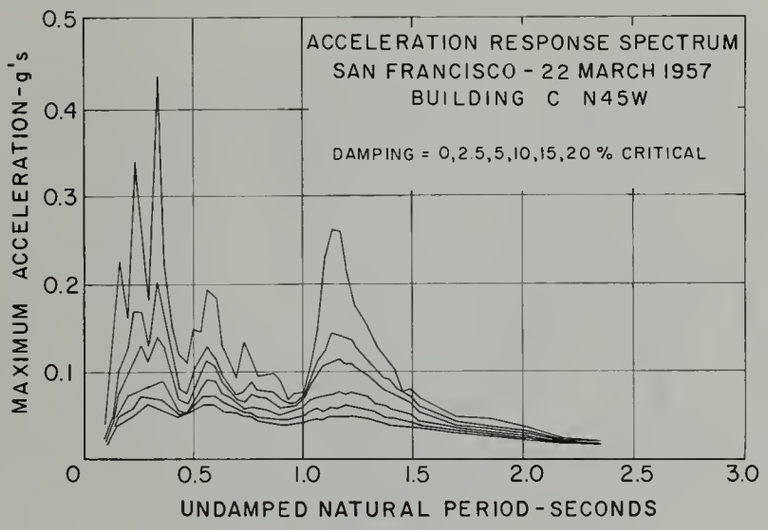
ACCELERATION RESPONSE SPECTRUM
SAN FRANCISCO - 22 MARCH 1957
BUILDING C N45W
DAMPING = 0,2.5,5,10,15,20 % CRITICAL
MAXIMUM ACCELERATION - g's
UNDAMPED NATURAL PERIOD - SECONDS

FIGURE 23.

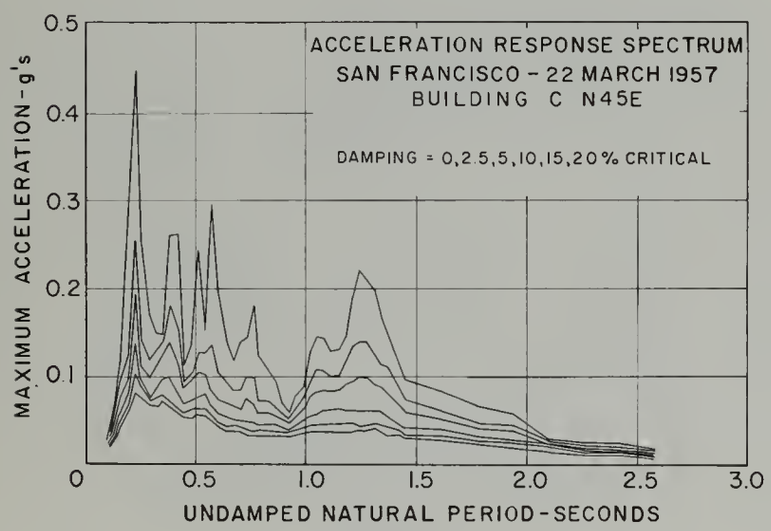
ACCELERATION RESPONSE SPECTRUM
SAN FRANCISCO - 22 MARCH 1957
BUILDING C N45E
DAMPING = 0,2.5,5,10,15,20 % CRITICAL
MAXIMUM ACCELERATION - g's
UNDAMPED NATURAL PERIOD - SECONDS

FIGURE 24.

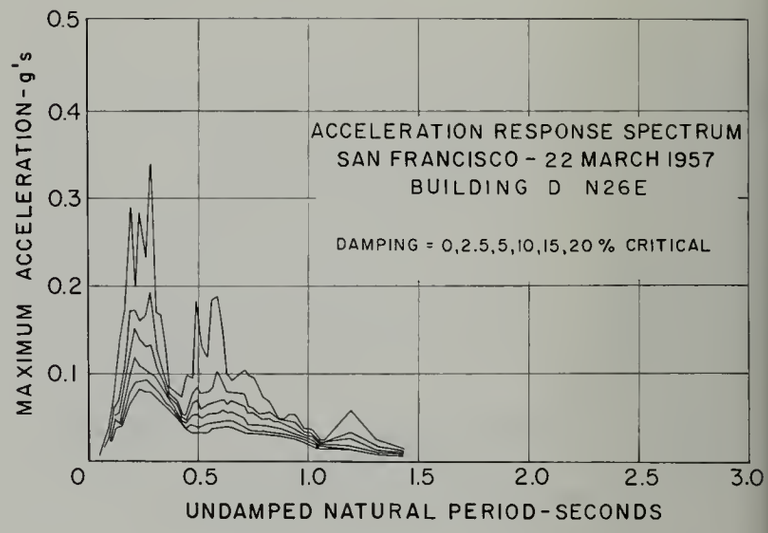
ACCELERATION RESPONSE SPECTRUM
SAN FRANCISCO - 22 MARCH 1957
BUILDING D N26E
DAMPING = 0,2.5,5,10,15,20 % CRITICAL
MAXIMUM ACCELERATION - g's
UNDAMPED NATURAL PERIOD - SECONDS

FIGURE 25.

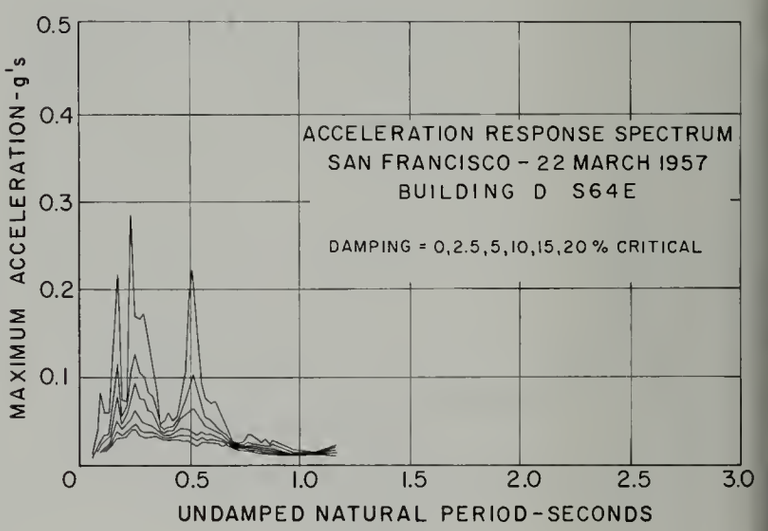
ACCELERATION RESPONSE SPECTRUM
SAN FRANCISCO - 22 MARCH 1957
BUILDING D S64E
DAMPING = 0,2.5,5,10,15,20 % CRITICAL
MAXIMUM ACCELERATION - g's
UNDAMPED NATURAL PERIOD - SECONDS

FIGURE 26.

magnitude and the duration, an interesting check on certain types of structural response may be obtained.

It thus seems likely that a number of interesting studies could be based on the strong-motion data from this earthquake. For this reason it is believed to be desirable to make available complete velocity and acceleration response spectrum curves for all of the strong-motion accelerograms.

In figure 1 is shown the distribution of the strong motion accelerometer stations of the United States Coast and Geodetic Survey. Only those stations are included from which records were obtained during the earthquake of 22 March 1957 which had acceleration magnitudes of structural significance. On this same figure is shown the instrumental epicenter as reported by the Seismographic Station of the University of California, Berkeley. Additional information from foreshocks and aftershocks has indicated the approximate distance along the fault zone involved in the major tearing action. Based on this information from the Seismographic Station, an estimated center of the torn zone has been indicated on figure 1 as the approximate origin of the major disturbance. From the same data it was estimated that the average depth of the torn area was 5 miles. This depth is not negligible compared with the distances from the epicenter to the strong-motion stations, and hence on the map the true straight-line distances from the source of major disturbance to the various strong-motion stations have been shown.

In figures 2-6 the horizontal components of ground acceleration as traced from the reproductions of the original photographic records from the strong-motion accelerometers are shown. These figures have all been arranged to have the same acceleration scale, so that the relative magnitudes at the various stations may be readily compared. It should be noted, however, that the time scales differ somewhat, as it was not feasible to completely replot the accelerograms.

In figures 7-16 the maximum relative velocity response spectra are shown for the various stations. These spectrum curves have been computed using the Electric Analog Spectrum Analyzer of the California Institute of Technology (Caughey and Hudson, 1955; Housner and McCann, 1949), and the data are presented in the standard form which has been used in preceding reports (Housner and Martel, and Alford, 1953; Housner, 1952, 1956). The maximum relative velocity response spectrum is defined as the maximum relative velocity between the ground support and the mass of a single degree of freedom spring-mass system of specified natural period and damping (Hudson, 1956).

In figures 17-26 the maximum acceleration response spectrum curves are shown. This is defined as the maximum absolute acceleration of the mass of a single degree of freedom spring-mass system of specified natural period and damping, and has been computed from the velocity spectra as obtained above (Hudson, 1956).

It will be observed from all of the spectrum curves that the influence of damping in reducing the peak values was not as marked in this earthquake as in more typical earthquakes. This was a consequence of the short duration of the earthquake, and of the fact that the maximum structural responses thus occurred near the start of the motion, before damping had an opportunity to dissipate much energy. Such records emphasize again the importance which damping may have in the structural problem.

Based on the above spectrum curves, a complete analysis of the spectrum intensities at the various stations has been made, as well as a calculation of the earthquake magnitude determined from the energy released by the earthquake (Hudson and Housner, 1958).

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EXPLANATION

Cretaceous-Upper Jurassic

Acid intrusive rocks; includes leucogranite and pegmatite dikes directly associated with the granodiorite.

Granodiorite; contains minor acid intrusive rocks and possibly hybrid granitic rocks.

CARBONIFEROUS
Calaveras group

Carbonate rocks undivided; includes crystalline limestone, dolomite and dolomitic limestone, much of which is intensely brecciated and sheared. Also includes minor amounts of other Calaveras rocks, as well as small dikes and sills.

Foliated non-carbonate rocks includes quartz-mica schist, micaceous quartzite, metacherl, quartz-mica hornfels and metabasic rocks with localization of migmatite(m) adjacent to granodiorite. Also contains impure, brecciated and sheared carbonate rocks. Much of unit is highly sheared and brecciated. Includes numerous dikes and sills.

Contact (dashed where approximately located).

Concealed contact.

Strike and dip of beds (tops of beds not determined)

Strike of vertical beds.

Strike and dip of schistosity and cleavage.

Strike of vertical schistosity and cleavage.

Generalized strike and dip of crumpled beds or foliation

Geology by Earl W. Hart, 1955–58.
Base map from U.S.G.S. Standard Quadrangle, 1949.

Scale in miles
Contour interval 50 feet

GEOLOGIC MAP OF A PORTION OF THE SOUTHERN HALF OF THE STANDARD QUADRANGLE, TUOLUMNE COUNTY, CALIFORNIA

92322-C

EXPLANATION

Strike and dip of schistosity and cleavage

Strike of vertical schistosity and cleavage

Strike and dip of beds and contacts between rock types (type of beds not determinable)

Strike of vertical beds and contacts

Generalized strike and dip of crumpled and crenulated beds; includes foliation of the migmatite

Strike and dip of joint or other rock

Contact between rock types, dashed where approximately located

ROCK TERMS

Limestone - medium- to coarse grained carbonate rock composed mostly of calcite

Dolomite - medium- fine grained carbonate rock composed mostly of dolomite

Schist - composed mainly of quartz, biotite and muscovite, includes bands of microscopic quartzite

Metachert - thinly bedded, microscopic, metamorphosed chert

Hornfels - fine grained quartz mica rock, granoblastic texture modified by shearing

Migmatite - foliated calc-carbonate rocks intimately injected with granitic material and generally contorted

Greenish limestone - thinly laminated or bedded sequence of limestone and schist

Metabasic rock - hornblende or biotite-rich rocks of igneous origin, generally has inclusions of limestone; contacts display colloidal, agglomeratic, and contact features

Diorite dikes - gray-green to black dikes and sills; too numerous and widespread to be shown on this map

Granitic dikes - includes leucogranite and pegmatite dikes, sometimes found only in north part of the area map

Geologic mapping 1948-1950 by Earl M. and Oliver E. Bonnichsen, Jr. and Frederick G. Stone

0 200 400
Scale in feet

N

Section 19, T 1N, R 16E
Section 30, T 1N, R 16E

Section 25, T 1N, R 15E
Section 36, T 1N, R 15E

Section 30, T 1N, R 16E
Section 31, T 1N, R 16E

Limestone with clayey dolomite

Dolomite and limestone

Massive dolomite

Massive dolomite

Massive limestone

Massive dolomite

Massive limestone

Limestone and dolomite

Massive limestone

Massive dolomite

Massive limestone

Limestone and dolomite

Massive dolomite

Massive limestone

Limestone and dolomite

Massive dolomite

Massive limestone

Limestone and dolomite

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120°22'30"

R.15 E. R.16 E.

120°15'

TO SONORA

TO STANDARD
TO SONORA

TO STANDARD
TO SONORA

TO TUOLUMNE
TO STANDARO

TO TUOLUMNE

TO JAMESTOWN

TO WARDS FERRY BRIOGE

Childress Ranch

Murphy Ranch

Musante Ranch

Mayhall Ranch

Eastman Ranch

Wards Ferry Schaal

Hawkins Ranch

Baker Ranch

Sudall Ranch

Waodham Ranch

T. 1 N.
T. 1 S.

37°52'30"

120°22 30"

R.15E. R.16E.

120°15'

92322-C

EXPLANATION

grd — Granadiorite and assaciated intrusive rocks

Majar masses af carbonate rock shawing lacatian af limestane depasits (1 ta 11) and dalamite depasits (12 to 16). 'ls' and 'd' indicate ather limestone and dalamite occurrences of possible value, but not evaluoted. 'dl' indicotes dolomitic limestane and mixtures af limestane, dalamite, and dalamitic limestane.

lPcs — Essentially nan-carbanate racks, includes schist, metachert, hornfels, quartzite, migmatite, metabasic racks, small intrusive sheets, and various impure and minar carbanate rock accurrences.

Lacalities from which samples were taken for chemical analyses (see text far details)

SCALE
0 500 1000 2000 4000 FEET

ECONOMIC MAP OF A PORTION OF THE SOUTHERN HALF OF THE STANDARD QUADRANGLE, TUOLUMNE COUNTY, CALIFORNIA

SHOWING THE POTENTIALLY ECONOMIC DEPOSITS OF LIMESTONE AND DOLOMITE AND THE MAJOR CARBONATE MASSES